OPTIMIZING WORK ZONE PRACTICES FOR HIGHWAY CONSTRUCTION PROJECTS

BY

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DISSERTATION

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ABSTRACT

Recent studies indicate that work zones suffer from an increasing trend of deaths and injuries in and around the highway construction areas with an average of 745 fatalities and 40,700 severe injuries per year. To control and minimize work zone fatalities and injuries, the Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO), and many state Departments of Transportation (DOTs) are seeking to improve the design practices of work zones to reduce work zone crashes. To support this vital and pressing highway safety goal, this research study focuses on analyzing and optimizing existing work zone practices and exploring the effectiveness and efficiency of innovative temporary rumble strips that can be used to minimize crashes in and around highway construction and maintenance projects.

The research objectives of this study are to: (1) provide enhanced understanding of the impact of work zone parameters and innovative temporary traffic control devices on the safety of highway construction zones; (2) analyze work zone crashes and current practices to identify potential layout parameters that impact work zone crash occurrence; (3) investigate and quantify the impact of work zone layout parameters on the risk and cost of crash occurrence; (4) optimize work zone setup parameters to minimize total work zone costs including agency, user delay, and expected crash costs; (5) conduct field experiments to analyze the efficiency and constructability of various arrangements of temporary rumble strips prior to and at the edge of work zones; and (6) study and enhance the effectiveness of temporary rumble strips in alerting inattentive drivers prior to and at the edge of work zones.

In order to achieve these objectives, the study is conducted in seven major tasks that focus on: (1) conducting a comprehensive literature review; (2) collecting and fusing all available data and reports on work zone crashes in Illinois; (3) analyzing work zone crashes and identifying the probable causes and contributing factors; (4) identifying the impact of layout parameters on risk of crash occurrence; (5) developing an optimization model to minimize total work zone costs including agency cost, user delay cost, and expected work zone crash cost; (6) performing field experiments on temporary rumble strips and evaluate the efficiency of utilization on site; and (7) evaluating the effectiveness of temporary rumble strips prior and at the edge of work zones.

The main research developments of this study are expected to have significant impacts on (1) identifying potential work zone parameters and contributing causes that impact work zone crash occurrence; (2) estimating the probability of work zones to encounter severe crashes; (3) quantifying the impact of work zone parameters on the risk levels of crash occurrence; (4) estimating the monetary value of work zone crashes based on work zone layout parameters; (5) searching for and identifying optimal work zone setup solutions that specify segment length, operating speed, TTC policy, and concrete barrier at different operation staring times; (6) developing new efficient prototypes of temporary rumble strips to be utilized prior to and at the edge of work zones; and (7) developing practical guidelines for effective design arrangements of temporary rumble strips. These new developments hold a strong promise to: (a) improve work zone safety for both the travelling public and construction workers; (b) improve current work zone layouts, strategies, and standards; (c) provide a baseline for controlling the risk of crash occurrence due to highway work zones; (d) assist construction planners in identifying optimal work zone setups for highway construction; (e) direct the development of practical recommendations for efficient and effective design arrangements of temporary rumble strips; and (f) reduce work zone crashes in the work area through the implementation of practical temporary rumble strips arrangements.

To my parents: Malak Mansour and Maged Elghamrawy

You are the first and greatest teachers and supporters of my lifetime

To my wife: Engy Eltir and to my son: Omar Elghamrawy

You are the true measure of my accomplishment

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Work zone safety is a major concern for the Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO) as well as state Departments of Transportation (DOTs). Recent data indicates that highway construction and maintenance work zone crashes cause an average of 745 fatalities and 40,700 severe injuries per year in the USA (FARS 2009) as shown in Figure 1.1. In Illinois, the total number of fatalities caused by work zone crashes from 1995 to 2007 is shown in Figure 1.2.

To control and minimize the aforementioned work zone fatalities and injuries, the Federal Highway Administration (FHWA), and American Association of State Highway and Transportation Officials (AASHTO) are seeking to improve the design practices of work zones that can directly reduce work zone crashes (Mahoney et al. 2007). Similarly, many state Departments of Transportation (DOTs) developed work zone safety and mobility policies to reduce work zone crashes (IDOT 2002; TxDOT 2009; Caltrans 2006; FHWA 2009b). For example, the Illinois Department of Transportation (IDOT) developed and implemented an important Safety Engineering Policy 3-07 that recommended a number of strategies to improve work zone safety, including (1) identifying current contributing factors that cause injury and fatal work zone crashes; and (2) adding temporary rumble strips for future implementation within and prior to work zones (ICHSP 2005).

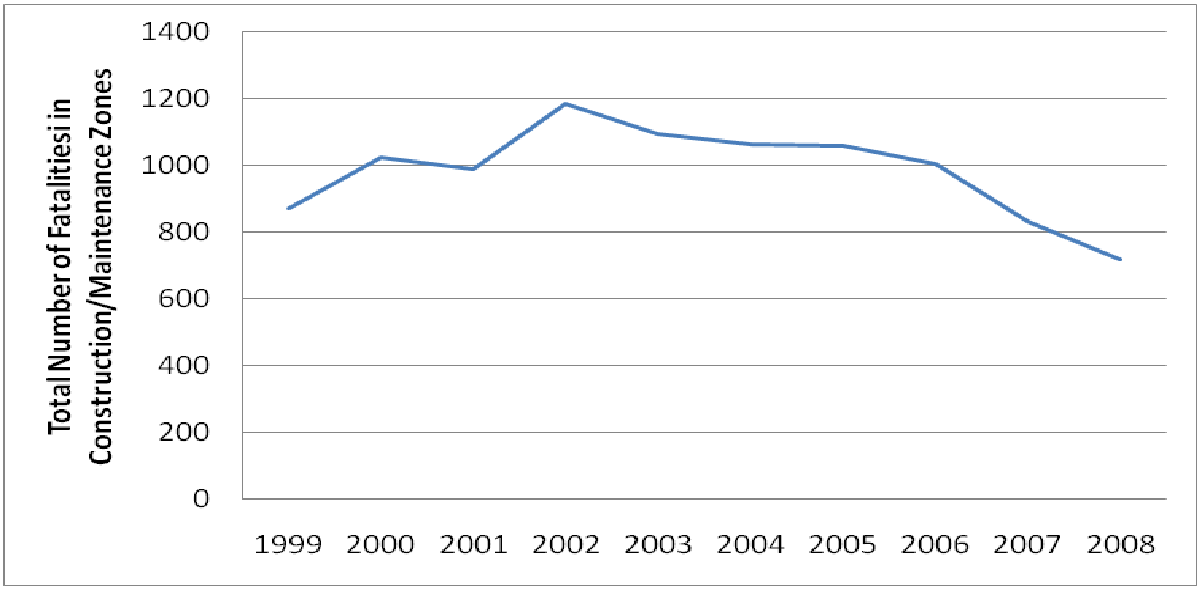


Figure 1.1 Total number of fatalities in Construction/Maintenance Zones in the USA (FARS 2008)

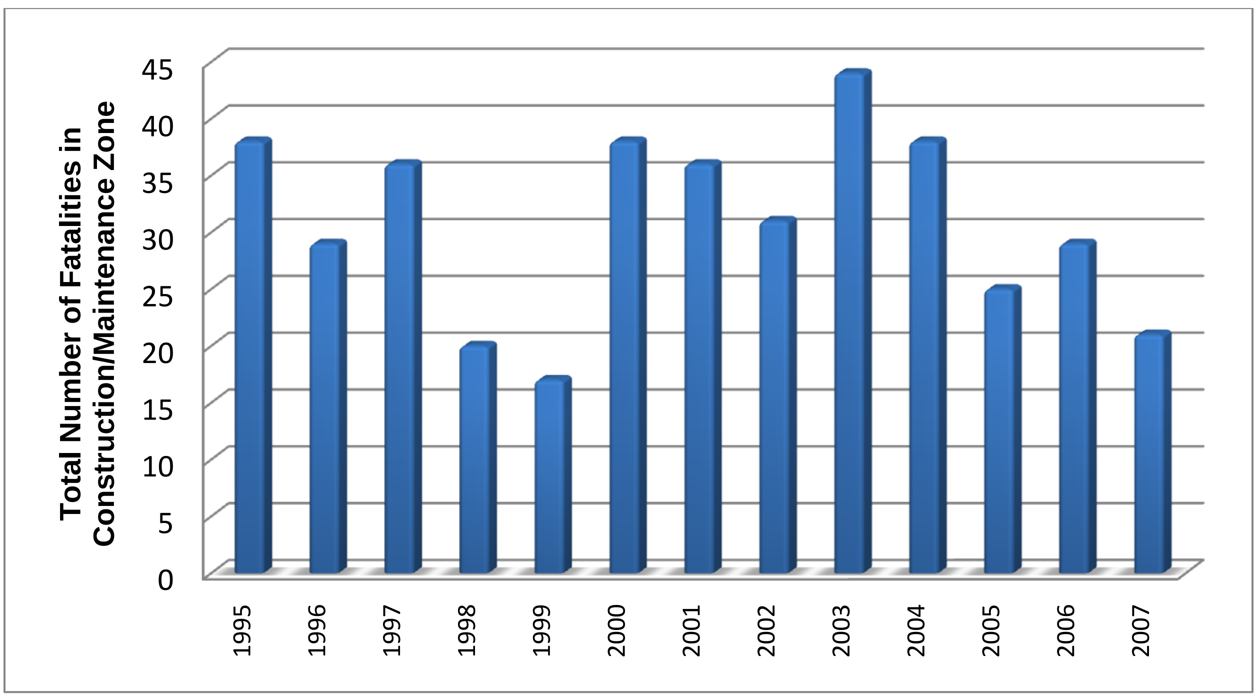


Figure 1.2 Total number of construction/maintenance zones fatalities in Illinois from 1995 to 2007 (FARS 2008)

1.2 PROBLEM STATEMENT

In order to investigate and enhance current and future work zone safety during highway construction operations, this study focuses on four important research thrusts: (1) analyzing and identifying contributing factors that cause injury and fatal work zone crashes; (2) investigating and quantifying the impact of work zone layout parameters on the risk and cost of crash occurrence; (3) evaluating and optimizing potential trade-offs between minimizing expected work zone crash cost while minimizing agency and user delay costs; and (4) studying the efficiency and effectiveness of future implementation of temporary rumble strips prior to and at the edge of work zones.

First, a number of research studies investigated and analyzed fatal and injury work zone crashes to identify factors contributing to unsafe conditions caused by work zones (Daniel et al. 2000; Garber and Zhao 2002; Mohan and Zech 2005). Other studies analyzed the impact of work zone design parameters on traffic safety and mobility (Daniel et al. 2000; Bryden and Mace 2002; Garber and Zhao 2002; Mohan and Zech 2005; Mahoney et al. 2007; Harb et al. 2008). The National Cooperative Highway Research Program (NCHRP) report 581 developed guidelines for the design of construction work zone geometric features including horizontal and vertical alignment, cross-sectional features, and temporary concrete barrier placement (Mahoney et al. 2007). The NCHRP report 476 recommended guidelines to help transportation agencies develop and implement plans for night work zones (Bryden and Mace 2002). Despite the significant contributions of the aforementioned studies, there is little or no reported research that studied the impact of work zone characteristics such as layout, type, duration, Temporary Traffic Control (TTC) devices, traffic volumes, median types, lane width, and vision obstructions on work zone crashes (El-Rayes et al. 2010).

Second, available research on traffic management plans (TMP) for work zones developed a number of models to estimate the queue length, travelers delays, and work zone capacity (Chien and Schonfeld 2001; Jiang and Adeli 2004; Yulong and Leilei 2007). These models such as QUEWZ (Queue and User Cost Evaluation of Work Zones) and QuickZone are used primarily to estimate the road user delay costs based on the average speed, AADT, and work zone capacity (Jiang and Adeli 2004). These models, however, did not analyze or quantify the impact of work zone layout parameters on the risk or the cost of crash occurrence.

Third, various methodologies have been developed to calculate work zone capacity, traffic delay costs, and work zone costs based on work zone characteristics (Benekohal 2003; Jiang and Adeli 2003; Karim and Adeli 2003). These models, however, have a number of limitations including their inability to consider: (1) significant work zone decision variables such as work zone speed limit, type of temporary traffic control (TTC) measures, and barrier type as they focused only on the two decision variables of work zone segment length and starting time; (2) the impact of work zone speed limit, highway free flow speed, and type of construction activity on work zone capacity as they considered it as a separate input data; (3) the traffic risks caused by work zones and the combined impact of their setup parameters on the probability of crash occurrence; and (4) the impact of the total project length on the optimization procedure as they focused only on one day short-term construction projects which limits the applicability of the model.

Fourth, several state DOTs utilize different sets of temporary rumble strips that are generally placed in different patterns in advance of highway segments where reduced speed or elevated driver alertness is required (Zech et al. 2005). Research studies have been conducted to study the effectiveness of rumble strips in two main areas: (1) quantifying the context of rumble strips application in terms of minimizing run-off-the-road and intersection crashes (Miles and Finley 2007), and (2) investigating the effect of rumble strips characteristics on alerting inattentive drivers (Fontaine and Carlson 2001; Miles and Finley 2007; Meyer 2000; Morgan 2003). Despite the significant contributions of the aforementioned studies, the effectiveness and constructability of various arrangements of temporary rumble strips prior to and at the edge of work zones have not been investigated.

To address the aforementioned research gaps and to maximize work zone safety, there is a pressing need to conduct additional research that focus on: (1) providing better understanding of the contributing factors that cause injury and fatal work zone crashes; (2) creating new knowledge on and quantifying the impact of work zone layout parameters on the risk and cost of crash occurrence; (3) developing novel optimization models that are capable of searching for and identifying optimal work zone setup solutions that minimize total work zone costs; and (4) analyzing the efficiency and effectiveness of utilizing new and innovative traffic control devices such as temporary rumble strips.

1.3 RESEARCH OBJECTIVES

The primary goal of this study is to create new knowledge and develop novel models that address the aforementioned research needs in order to maximize work zone safety while minimizing highway construction costs. To accomplish this goal, the objectives of this study, along with its relevant research questions and hypotheses are summarized as follows:

<u>Objective 1:</u> Provide enhanced understanding of the impact of current work zone parameters and innovative temporary traffic control devices on the safety of highway construction zones.

<u>Research Questions:</u> What are the current practices of work zone layouts and strategies? What are the typical temporary traffic control devices and transportation management plans for work zone areas? What are the merge techniques and queue detection systems used in and around construction areas? What are the relevant and recent federal and US DOTs rules on work zone safety and mobility? What are the statistical methods and factors used for work zone crash data reporting and analysis? What are the basic characteristics of temporary rumble strips?

<u>Hypothesis:</u> The investigation of existing and futuristic practices and standards of work zone layouts and traffic control devices will ensure that research developments are aimed at addressing the most pressing needs to maximize highway construction safety.

<u>Objective 2:</u> Analyze work zone crashes and current practices to identify potential layout parameters that impact work zone crash occurrence and to develop crash severity indices to represent the probability of work zone to encounter severe crashes.

<u>Research Questions:</u> What are the available data sources of crashes in Illinois? How data from different source can be fused and integrated into single comprehensive dataset? What are the differences and similarities among fatal, multi-vehicle, and single-

vehicle work zone crashes? What are the probable causes and contributing factors of work zone crashes? What are the possible correlations among work zone parameters? How crash severity indices can be developed to represent the severity of work zone crashes? What recommendations can be drawn out of these analyses? What are IDOT resident engineers' recommendations to improve work zone layouts? What are IDOT resident engineers' recommendations to utilize new and innovative temporary traffic control devices in and around work zones?

Hypothesis: The frequency and severity analysis of different types of work zone crashes can be used to identify potential work zone parameters and contributing causes that impact work zone crash occurrence. The development of work zone crash severity indices can be used by construction planners to estimate the potential occurrence of severe work zone crashes. The results of work zone crash analysis along with IDOT resident engineers' suggestions can be used to develop practical guidelines for improving current work zone practices.

Objective 3: Investigate and quantify the impact of work zone layout parameters on the risk of crash occurrence and develop a new metric to estimate the monetary value of work zone crash cost.

Research Questions: What are the risk levels of work zone parameters such as layouts, types, and duration on crash occurrence? What are the risk levels of reduced lane width, shoulder usage, and vision obstructions on crash occurrence? What is the relative importance of work zone parameters according to their influence on the safety of work zone? What is the monetary value of work zone crashes based on layout hazards?

Hypothesis: The investigation of highway work zone parameters will be used to objectively quantify risk levels of various layout parameters and develop a new metric for estimating the monetary value of crash cost.

Objective 4: Optimize work zone setup parameters to minimize total work zone costs including agency, user delay, and expected crash costs.

Research Questions: What are the metrics required to quantify the safety of work zones? What are the metrics required to calculate total work zone costs in terms of user delay, crashes, and maintenance costs? How can advanced computing tools be utilized to provide optimal trade-offs among the conflicting work zone objectives of minimizing work zone crash cost while minimizing total work zone construction and user delay costs.

Hypothesis: An optimization model for highway work zones can be used to search for and identify optimal work zone setup solutions that minimize total work zone costs.

Objective 5: Conduct field experiments to analyze the efficiency and constructability of various arrangements of temporary rumble strips prior to and at the edge of work zones.

Research Questions: How to conduct controlled field experiments on temporary rumble strips to simulate the typical arrangements in work zones? How rumble strips characteristics affect the efficiency and practicality of use in work zones? How temporary rumble strips can be used at the edge of work zones? How temporary rumble strips can be connected together in sets to facilitate the placing and removal processes?

Hypothesis: Testing and analyzing various arrangements of temporary rumble strips of different types will direct the development of new prototypes for efficient utilization of temporary rumble strips prior to and at the edge of work zones. The new prototype of utilizing temporary rumble strips at the edge of work zones will alert inattentive drivers if they encroach into the work area in a similar way that permanent rumble strips are used to alert drivers when they drift off the road to reduce the risks of work zone crashes.

Objective 6: Study and enhance the effectiveness of temporary rumble strips in alerting inattentive drivers prior to and at the edge of work zones.

Research Questions: What is the procedure of evaluating the effectiveness of various patterns of temporary rumble strips? What are the parameters that impact the auditory stimulus experienced by motorists? What are the possible locations to place temporary rumble strips within work zone layouts?

Hypothesis: The results of the field experiments can be used to identify the impact of rumble strips characteristics on the levels of sound generated and experienced by motorists inside the cabin of vehicles.

1.4 RESEARCH METHODOLOGY

In order to achieve the aforementioned objectives, a research methodology is proposed as shown in Figure 1.3. The proposed methodology consists of seven main research tasks that are designed to: (1) conduct a comprehensive literature review; (2) collect and fuse all available data and reports on work zone crashes in Illinois; (3) analyze work zone crashes and identify the probable causes and contributing factors; (4) identify the impact of layout parameters on risk of crash occurrence; (5) develop an optimization model for highway construction and maintenance projects to minimize total work zone costs; (6) perform field experiments on temporary rumble strips and evaluate the efficiency of utilization on site; and (7) evaluate the effectiveness of temporary rumble strips prior and at the edge of work zones.

1.4.1 Task 1: Conduct a comprehensive literature review

This task focuses on conducting a comprehensive literature to establish baseline knowledge of existing research and practices in investigating work zone characteristics and their effect on the frequency and severity of work zone crashes. The work in this research task is organized in the following subtasks:

1- Investigate work zone layouts, strategies, and temporary management plans.
2- Identify temporary traffic control devices and their typical applications.
3- Explore work zone parameters, merge techniques, and queue detection systems.
4- Collect federal as well as state departments of transportation rules and standards of work zone safety and mobility.
5- Examine methods used for work zone crash data reporting and analysis to determine work zone crash characteristics and contributing factors.
6- Explore advanced statistical methods used for analyzing roadway crashes.

1.4.2 Task 2: Collect and fuse available data and reports on work zone crashes in Illinois

This task involves gathering all available data and reports on work zone crashes in Illinois from all available sources and fusing them into single comprehensive dataset. The research work in this task is divided into three subtasks:

1- Collect crash data including (1) National Highway and Traffic Safety Administration (NHTSA) crash data; (2) Highway Safety Information System (HSIS) crash data; and (3) police crash reports and integrate them into a single comprehensive dataset.
2- Extract fatal and injury work zone crashes and investigate any variations of the data collected and correct them.
3- Reorganize and regroup work zone crash variable observations into comprehensive analytical form.

1.4.3 Task 3: Analyze Work Zone Crashes and Identify Contributing Factors

In this task, a comprehensive analysis of work zone crashes is conducted to identify the probable causes and contributing factors of work zone crashes in Illinois followed by the development of three crash severity indices to represent the probability of a work zone to encounter severe crashes. The research work in this task is divided into five subtasks:

1- Conduct crash frequency analysis to investigate and compare the impact of work zone parameters on the frequency and severity of: (a) fatal work zone crashes; (b) multi-vehicle injury crashes; and (c) single-vehicle injury crashes.
2- Identify all possible correlations among work zone crash parameters in the gathered dataset.
3- Investigate probable causes and contributing factors of work zone crashes in Illinois.
4- Develop crash severity indices that represent the probability of a work zone to cause severe crashes.
5- Develop guidelines to improve work zone practices in terms of: (a) layout; (b) strategy; (c) standards; and (d) temporary traffic controls.

1.4.4 Task 4: Identify the impact of layout parameters on the risk of crash occurrence

The research work in this task is focused on quantifying the impact of work zone layout parameters on the risk of crash occurrence. The impact of work zone parameters is quantified using the results of: (1) site visits of different types of work zones; and (2) an online survey on work zone practices developed to collect IDOT resident engineers' perceptions of the risk level associated with various work zone parameters. Based on the results of work zone crash analysis and survey results, a new metric for estimating the monetary value of work zone crash costs is developed. The work in this task is divided into four sub-tasks:

1- Conduct site visits for three different types of construction work zones to gather data on current practices typically utilized in and around highway work zones.

2- Conduct an online survey that includes all potential risk parameters of work zones and distribute it to Illinois resident engineers.

3- Identify the impact of work zone parameters on the risk of crash occurrence using survey results.

4- Develop a metric to estimate the monetary value of work zone crashes.

1.4.5 Task 5: Develop an optimization model for highway construction zones

In this task, a new optimization model is developed to minimize total work zone costs including: (1) agency/construction cost; (2) user delay cost; and (3) crash cost. The model is designed to find an optimal solution for five main work zone decision variables: (a) work zone segment length; (b) work zone speed limit; (c) starting time; (d) Temporary Traffic Control (TTC) policy; and (e) barrier type. The research work in this task will be performed in three subtasks:

1- Formulate the model including its decision variables, objective function and cost metrics.

2- Implement the model using genetic algorithms in a C++ object oriented environment.

3- Evaluate the performance of the developed optimization model and demonstrate its capabilities in optimizing work zone setup.

1.4.6 Task 6: Perform field experiments on temporary rumble strips and evaluate the efficiency of their utilization on site

A number of controlled field experiments on temporary rumble strips are conducted in this task to analyze the efficiency and constructability of various arrangements prior to and at the edge of work zones. The research work in this task is divided into five subtasks to test and examine the efficiency of three commonly used temporary rumble strips.

1- Conduct a comprehensive literature review on temporary rumble strips.
2- Setup the experiment location and prepare the site.
3- Identify temporary rumble strips types and testing vehicles.
4- Analyze the installation and removal processes of various types of different arrangements.
5- Develop new prototypes of utilizing temporary rumble strips at the edge of work zones.

1.4.7 Task 7: Evaluate the effectiveness of temporary rumble strips prior and at the edge of work zones

The measured sound levels inside the cabin of three different vehicles traversing over 27 different arrangements of temporary rumble strips at different speeds are measured and analyzed to evaluate temporary rumble strips effectiveness. This task is performed in four subtasks:

1- Install temporary rumble strips and calibrate the sound level meter used in field to measure sound levels. Collect the readings of sound levels of different arrangements.
2- Evaluate the impact of temporary rumble strips geometries on the generated sound levels.
3- Conduct advanced statistical analysis to identify the correlated study parameters associated with each configuration.

4- Develop practical guidelines to improve the effectiveness of utilizing temporary rumble strips in work zones.

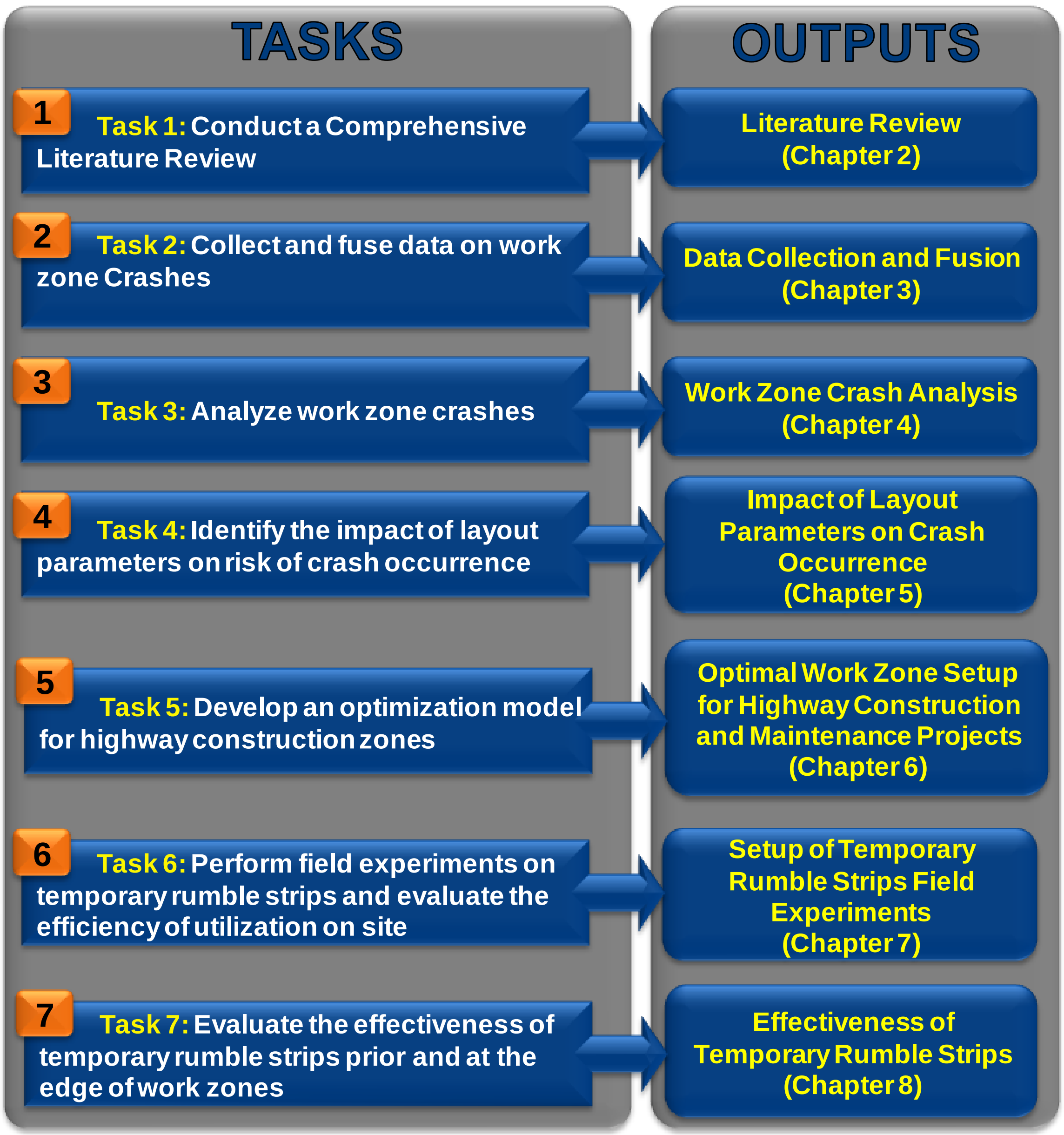


Figure 1.3 Research Tasks and Outputs

1.5 RESEARCH SIGNIFICANCE

The main research developments of this study are expected to have significant impacts on (1) identifying potential work zone parameters and contributing causes that impact work zone crash occurrence; (2) estimating the probability of work zones to encounter severe crashes; (3) quantifying the impact of work zone parameters on the risk levels of crash occurrence; (4) estimating the monetary value of work zone crashes based on work zone layout parameters; (5) searching for and identifying optimal work zone setup solutions that specify segment length, operating speed, TTC policy, and concrete barrier at different operation staring times; (6) developing new efficient prototypes of temporary rumble strips to be utilized prior to and at the edge of work zones; and (7) developing practical guidelines for effective design arrangements of temporary rumble strips. These new developments hold a strong promise to: (1) improve work zone safety for both the travelling public and construction workers; (2) improve current work zone layouts, strategies, and standards; (3) provide a baseline for controlling the risk of crash occurrence due to highway work zones; (4) assist construction planners in identifying optimal work zone setups for highway construction; (5) direct the development of practical recommendations for efficient and effective design arrangements of temporary rumble strips; and (6) reduce work zone crashes in the work area through the implementation of practical temporary rumble strips arrangements.

1.6 REPORT ORGANIZATION

The organization of this report and its relation to the main research tasks of this study is shown in Figure 1.3. Chapter 2 presents a detailed literature review that establishes baseline knowledge of existing research and different methodologies in investigating work zone characteristics and their effect on the frequency and severity of work zone crashes as well as exploring advanced statistical methods for analyzing roadway crashes. Sources of information included publications from professional societies, journal articles, on-line databases, and contacts from DOT's. In addition, work zone layouts, temporary traffic control devices and typical applications, work zone strategies, and work zone transportation management plans have been investigated.

Chapter 3 presents the data collected and fused from Illinois crash data sources. Illinois crash data were collected utilizing different crash sources, including the National Highway Traffic Safety Administration (NHTSA 2007), the Highway Safety Information System (HSIS 2009), and police crash reports. The chapter presents the methodology adapted for gathering and fusing work zone crash data from all these sources and the variations in the datasets. The subcategories of many work zone parameters were reorganized and regrouped in a more comprehensive analytical form.

Chapter 4 presents the results of the frequency and severity analysis of work zone crashes collected and reorganized in Chapter 3. A correlation analysis was first performed to identify correlations among the available crash variables in the gathered dataset to investigate probable causes and contributing factors of work zone crashes in Illinois. Then, further crash frequency analyses were conducted to investigate and compare the impact of work zone crash variables on the frequency and severity of fatal work zone crashes; multi-vehicle work zone crashes; single-vehicle injury work zone crashes. Three crash severity indices are developed to represent the probability of a work zone to cause severe crashes. The three work zone crash severity indices represent the probability of a work zone to encounter (1) severe injury crashes; (2) multi-vehicle crashes; and (3) multi-injury crashes. Finally, the chapter presents a set of practical recommendations to improve current work zone practices in terms of: (a) layout; (b) strategy; (c) standards; and (d) temporary traffic controls.

Chapter 5 presents the impact of work zone layout parameters on the risk of crash occurrence. First, the results of three site visits of different highway construction zones are presented. Then, the results and analysis of an online survey of work zone practices are discussed. The survey was conducted to collect Illinois resident engineers' perceptions of the risk level associated with 64 work zone parameters in order to objectively evaluate and control the risk of work zone crashes in Illinois. A new metric for estimating the monetary value of work zone crash costs is developed. The new metric is modeled based on the impact of work zone hazards that contribute to increasing the risk level of crash occurrence and the temporary traffic control policy adopted to mitigate that risk. Finally, the chapter presents IDOT resident engineers' recommendation to improve current work zone practices.

Chapter 6 presents the development of a novel optimization model for work zone setup of highway construction projects that is designed to find an optimal solution for five main work zone decision variables: work zone segment length, work zone speed limit, operation starting time, type of TTC, and barrier type. The model provides the capability of minimizing the total work zone cost of short- and long-term highway work zones which integrates three new metrics developed to calculate agency cost, user delay cost, and crash cost. The three cost metrics were modeled to estimate work zone costs at each construction hour using hourly traffic flow data. The optimization model was implemented using genetic algorithms (GAs) in a C++ objected oriented environment. In order to evaluate and refine the performance of the optimization model, an application example was then analyzed.

Chapter 7 presents the setup of field experiments conducted to study and evaluate the efficiency and constructability of temporary rumble strips prior to and at the edge of work zones. The chapter presents the experimental setup, site preparation, and study parameters followed by a detailed analysis of the efficiency of temporary rumble strips.

Chapter 8 presents the statistical analyses of field experiment data to evaluate the effectiveness of various arrangements of temporary rumble strips. The change in sound levels for various rumble strips arrangements and the knowledge gathered from the literature are used to evaluate the effectiveness of temporary rumble strips to be used prior and at the edge of work zones. Based on the main findings of field experiments, a set of practical guidelines have been developed to enhance the utilization of temporary rumble strips in terms of: (1) type; (2) patterns; (3) spacing; (4) vehicle type; (5) vehicle speed; and (6) location.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

A comprehensive literature review was conducted to establish baseline knowledge of existing research and practices in investigating work zone characteristics and their effect on the frequency and severity of work zone crashes. Literature pertaining to research studies conducted by state Departments of Transportation (DOTs) and Federal standards were also obtained. This chapter provides a summary of the collected information and organizes the literature review results in seven major sections: (1) work zone layouts and strategies; (2) temporary traffic control devices and typical applications; (3) work zone parameters and transportation management plans; (4) nighttime work zones and merge techniques; (5) federal rules of work zone safety and mobility; (6) literature review of work zone crash studies; and (7) literature review of statistical methods applicable for analyzing work zone crashes.

2.2 WORK ZONE LAYOUTS

The layout of a work zone must provide a clear separation between the travel and work activity spaces and provide buffer spaces for protecting motorists and workers who unintentionally stray from their intended areas (Bryden and Mace 2002). The work zone is divided into four areas: (1) advance warning; (2) transition; (3) activity; and (4) termination as shown in Figure 2.1 (MUTCD 2003).

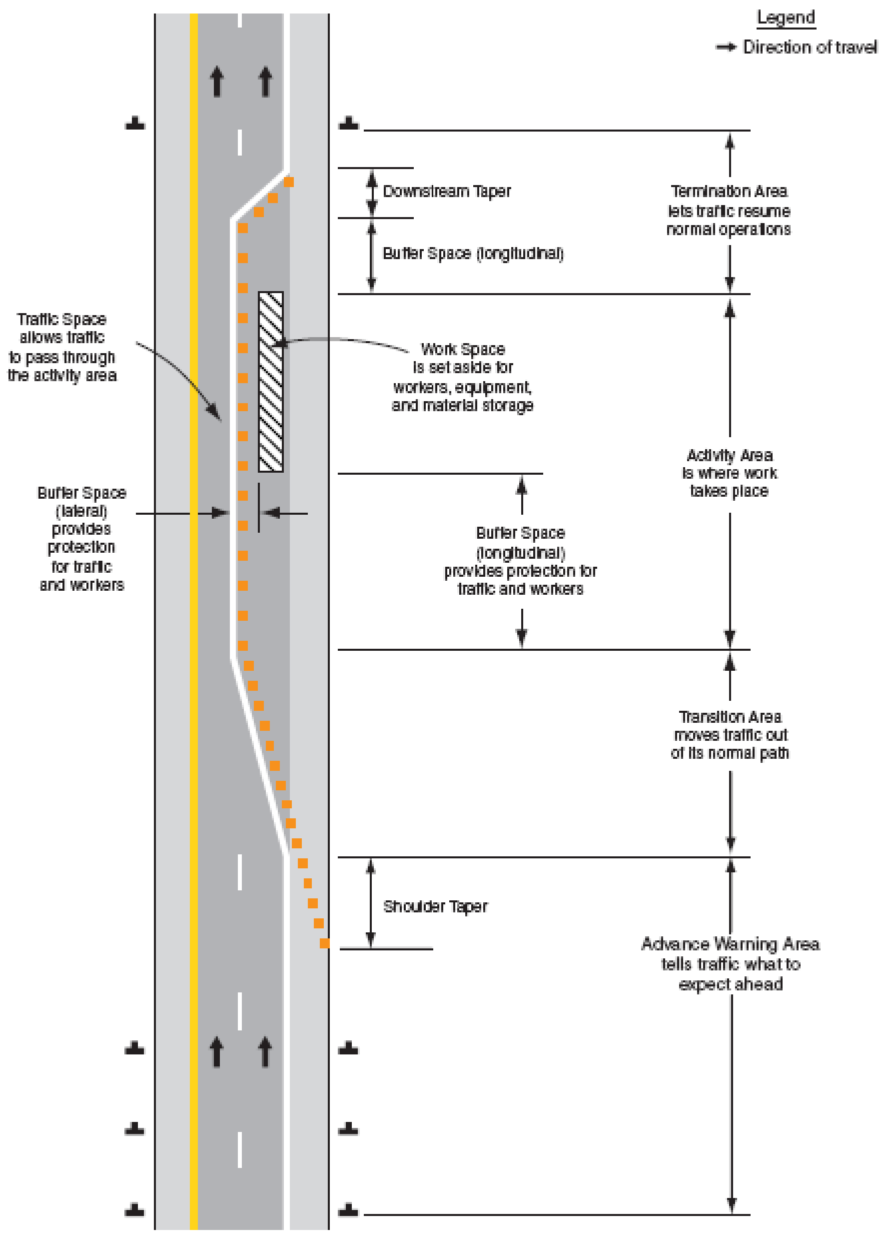


Figure 2.1 Major components of a temporary traffic control zone (MUTCD 2003).

2.2.1 Advance Warning Area

The advance warning area is the section of roadway where road users are informed about the upcoming work zone. Since two or more advance warning signs are regularly used, the advance warning area should extend 1,500 ft (450 m) or more for open highway conditions and it may extend on freeways and expressways as far as 0.5 mi (800 m) or more (MUTCD 2003). The effective placement of the first warning sign in advance of the taper in feet (meters) should be substantially long—from 8 to 12 times the speed limit in mph (1.5 to 2.25 times the speed limit in km/h) (MUTCD 2003).

2.2.2 Transition Area & Tapers

The transition area is the section of roadway where road users are redirected out of their normal path. Transition areas usually involve strategic use of tapers. Tapers are created by using a series of channelizing devices and in some cases pavement markings to move traffic out of the normal path. Figure 2.2 illustrates different types of tapers. The appropriate taper length (L) is determined using Tables 2.1 and 2.2, and the maximum distance in feet (meters) between devices in a taper should not exceed 1.0 times the speed limit in mph (0.2 times the speed limit in km/h) (MUTCD 2003).

Table 2.1 Formulas for Determining Taper Length (MUTCD 2003)

Speed Limit (S)	**Taper Length (L) Meters**
60 Km/h or less	L= $\frac{WS^2}{155}$
70 km/h or ore	L = $\frac{WS}{1.6}$

Speed Limit (S)	**Ta er Length (L) Feet**
4 mph or less	L= $\frac{WS^2}{60}$
45 mph or more	L = WS

Where: L = taper length S = posted speed limit
W = width of offset

Table 2.2 Taper Length Criteria for Temporary Traffic Control Zone (MUTCD 2003)

Type of Taper	**Taper length (L)**
Merging Taper	At least L
Shifting Taper	At least 0.5L
Shoulder Taper	At least 0.33L
One-Lane, Two-Way Traffic Taper	100 ft (30 m) maximum
Downstream Taper	100 ft (30 m) per lane

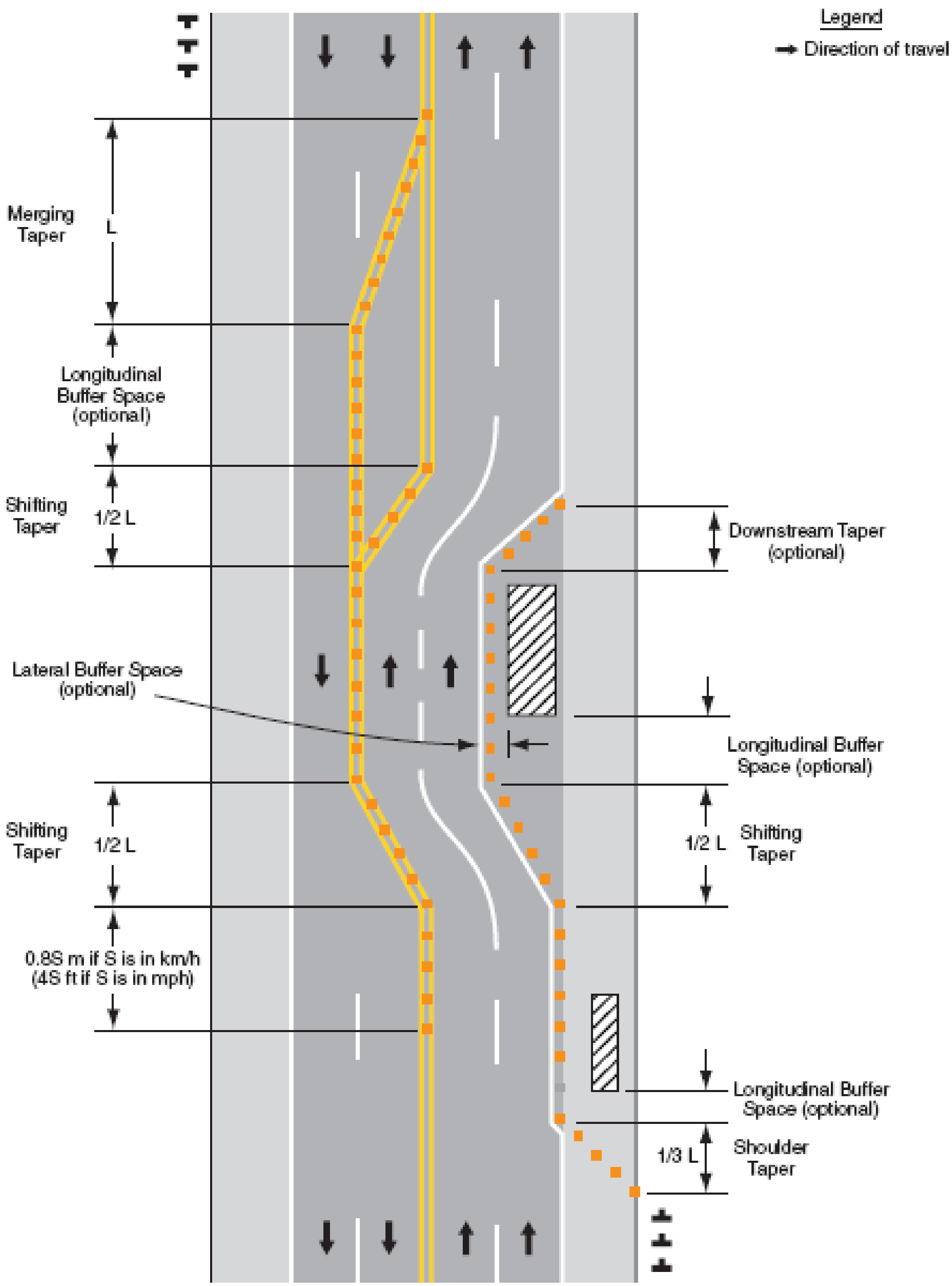


Figure 2.2 Different types of tapers and buffer spaces (MUTCD 2003)

2.2.3 Activity Area

The activity area is the section of the roadway where the work activity takes place. It is comprised of the work space, the traffic space, and the buffer space. The work space could be stationary or mobile depending on the progress of work. Buffer spaces, as shown in Figure 2.1, are positioned longitudinally and laterally with respect to the direction of traffic flow. The allowable values of the longitudinal buffer length are determined based on the allowable stopping sight distance which varies according to the design speed (MUTCD 2003).

2.2.4 Termination Area

The termination area is the section of the roadway that returns road users to their normal path. It extends from the downstream end of the work area to the last temporary traffic control (TTC) device, and it has been investigated by a research study that found it to have the least number of crashes in the work zone (Bai and Li 2006).

2.3 WORK ZONE STRATEGIES

A work zone strategy is developed to carry traffic through or around the facility under construction via a system of infrastructure and a set of temporary traffic controls (Mahoney et al. 2007). Nine strategies are widely employed for construction work zones on highways, and are outlined in the transportation management plans (TMP) for specific projects (IDOT 2002; Mahoney et al. 2007). These strategies include: (1) alternating one-way operation; (2) detour; (3) diversion; (4) full road closure; (5) intermittent closure; (6) lane closure; (7) lane constriction; (8) median crossover; and (9) use of shoulder. Each of these nine strategies has its own basic characteristics and offers a unique set of advantages and disadvantages, as summarized in Table 2.3

(IDOT 2002; Mahoney et al. 2007). The selection process of a work zone strategy is governed by many factors such as the number of lanes, geometric and structure design, highway and worker safety, accessibility, capacity and queues, constructability, and cost consequences (Mahoney et al. 2007).

Table 2.3 Summary of Work Zone Strategies – Advantages and Disadvantages (Mahoney et al. 2007)

Strategy	Advantages	Disadvantages
1- Alternating one-way operation	Low agency cost Flexible	Stopping of traffic Capacity reduction
2- Detour	Flexible Cost depends on detour plan	Capacity reduction Degrading of existing roads
3- Diversion	Traffic-work separation Low impact on traffic	Higher cost Right-of-way is required
4- Full road closure	Expedited construction Traffic-work separation	Another strategy is required High traffic impact
5- Intermittent closure	Flexible Low agency cost	Short-term work zones High traffic impact
6- Lane closure	Service maintained Low agency cost	Capacity reduced High traffic impact
7- Lane constriction	Low impact on traffic	Undesirable lane width
8- Median crossover	Traffic separation Low impact on traffic	Capacity reduced High cost
9- Use of shoulder	Low cost	displace disabled vehicles refuge

2.4 TEMPORARY TRAFFIC CONTROL DEVICES AND TYPICAL APPLICATIONS

Traffic control devices are defined as all signs, signals, markings, and other devices used to regulate, warn, or guide traffic, placed on, over, or adjacent to a roadway (MUTCD 2003). The MUTCD manual includes ten parts in which part 6 focuses on all Temporary Traffic Control (TTC) devices. When the regular function of the roadway is suspended, TTC planning provides movement continuity of motor vehicles, transit operations, and accessibility to property and utilities (MUTCD 2003). The Manual identifies a number of factors that govern the TTC planning, including: (1) type of highway; (2) road user conditions; (3) duration of operation; (4) physical constraints; and (5) the proximity of the work space or incident management activity to road users.

The Manual provides guidance on the use and implementation of diverse types of devices. A partial list of these devices includes: (1) temporary control signs; (2) arrow panels; (3) channelizing devices; (4) temporary raised pavement markers; (5) high-level working devices; (6) portable changeable message signs; (7) temporary traffic barriers; (8) delineators; (9) lighting devices; (10) crash cushions; (11) vehicle-arresting systems; (12) rumble strips; and (13) screens (MUTCD 2003). The implementation of TTC devices regularly follows agencies' objective guidelines for roadway safety, considering different factors such as traffic conditions, site conditions, traffic volume, and the cost effectiveness of candidate safety alternative devices (Wolff and Terry 2006).

The choice of TTC typical application needed for a construction site depends on the nature of the work (MUTCD 2003). The closer the work is to road users, the greater the number of TTC devices is needed. Forty-six typical work zone applications have been presented in the Manual with illustration of the signs required, and the detailed information for the order, location, and spacing of these signs. An example of a typical work zone application is the stationary lane closure on a divided highway, as shown in Figure 2.3 (MUTCD 2003). The distances A, B, and C for the typical applications are calculated using Table 2.4 (MUTCD 2003).

Table 2.4 Dimensions A, B, C used on Typical Application Diagrams (MUTCD 2003)

Road Type	**Distance Between Signs**		
	A	**B**	**C**
Urban (low speed)	100 ft	100 ft	100 ft
Urban (high speed)	350 ft	350 ft	350 ft
Rural	500 ft	500 ft	500 ft
Expressway/Freeway	1000 ft	1500 ft	2640 ft

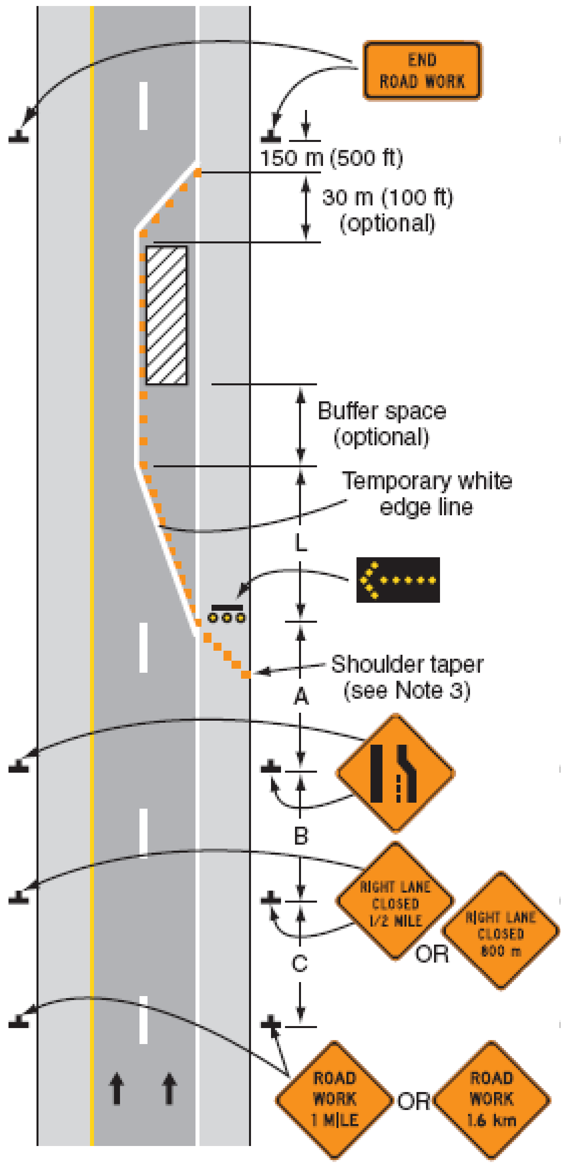


Figure 2.3 Stationary lane closure on divided highway (typical application 33) (MUTCD 2003)

2.5 WORK ZONE DESIGN PARAMETERS

The American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and state Departments of Transportation (DOTs) consider improving design practices of work zones as a high priority that can directly enhance work zone safety and mobility (Mahoney et al. 2007). The fifth edition of the AASHTO Policy on Geometric Design of Highways and Streets

"Green Book" contains the latest design practices for permanent highways and street facilities (AASHTO 2004). The AASHTO roadside design guide also provides current operating practices for roadside safety focusing on safety measures that can minimize the likelihood of serious injuries when a motorist runs-off the roadway (AASHTO 2002). Neither AASHTO manual provides detailed guidance for design criteria of highway work zone geometries (Mahoney et al. 2007), and accordingly many state DOTs have developed work zone safety and mobility policies (IDOT 2002; TxDOT 2009; Caltrans 2006; FHWA 2009b).

A number of research studies investigated the impact of work zone design parameters on traffic safety and mobility (Hauer 2000). For example, the NCHRP report 581 “Design of Construction Work Zones on High-Speed Highways”, investigated and developed guidelines for the design of construction work zone geometric features including horizontal and vertical alignment, cross-sectional features, and temporary concrete barrier placement (Mahoney et al. 2007). The study identified eight design principles that should guide work zone design decisions, namely: (1) safety impact to account for the probability of crash occurrence; (2) design consistency to avoid unexpected geometric conditions; (3) priority of how drivers process information from various sources; (4) speed reduction measures; (5) work zone design speed; (6) sight distance; (7) forgiving roadside; and (8) risk exposure principles that increases the probability of vehicle’s departure including construction equipment and materials, edge drop-off, severe roadside slopes, concrete barriers, and excavations (Mahoney et al. 2007).

In another study, NCHRP report 476 investigated and generated guidelines to help transportation agencies develop and implement plans for night work that help increase the safety of the motorists and the worker while minimizing waste and other problems associated with nighttime construction (Bryden and Mace 2002). The developed guidelines were designed to help users identify the minimum specification, setup, and maintenance of each nighttime work zone design element, including traffic control devices, barriers, lighting, and other safety features (Bryden and Mace 2002).

Other studies have identified a number of work zone design parameters that have a direct impact on work zone design decisions, including: (1) roadway functional classification (interstate, expressway, and principal arterial); (2) area type (urban, suburban, and rural); (3) traffic demand and travel characteristics (lanes affected, average daily traffic (ADT), expected capacity reduction, and level of service); (4) type of work (new construction, reconstruction, rehabilitation, or maintenance); (5) complexity of work (duration, length, and intensity); (6) climate of the region; (7) level of traffic interference with construction activity; and (8) potential impacts on local network and businesses (Karim and Adeli 2003; MUTCD 2003; Scriba et al. 2005).

2.6 WORK ZONE TRANSPORTATION MANAGEMENT PLANS (TMPS)

Transportation management plans (TMPs) for road projects are required for all federal-aid highway projects to study work zone impacts (Scriba et al. 2005). A full TMP includes the following three components (ICHSP 2005):

1- Traffic Control Plan (TCP): a plan of traffic control devices that shall be used for guiding traffic through a work zone, it is prepared for most construction and maintenance projects. This plan focuses on: (1) work zone traffic control; (2)

specific work zone strategy; (3) construction procedures; and (4) traffic demand on the facility under construction (Bryden and Mace 2002).

2- Public Information Plan (PIP): a plan of strategies that shall be implemented to inform the public of the expected impacts of a work zone.

3- Transportation Operation Plan (TOP): a plan of strategies that shall be implemented to mitigate work zone impacts.

2.7 NIGHTTIME WORK ZONES

Nighttime construction is recommended as a way to decrease the impact of construction operations on the traveling public and to shorten the duration of construction operations (Bryden and Mace 2002). Despite the advantages of nighttime construction, some studies indicated that it may create additional hazardous conditions for both drivers and construction personnel (El-Rayes et al. 2003). Existing nighttime construction specifications recommend a minimum level of average illuminance and light uniformity on site to ensure the availability of adequate lighting conditions for all planned nighttime construction tasks (Hyari and El-Rayes 2006; El-Rayes et al. 2007). A recent study developed a survey to identify associated nighttime problems that are mostly faced by resident engineers in the State of Illinois (El-Rayes et al. 2003). The survey indicated five nighttime lighting problems: (1) insufficient lighting; (2) lighting uniformity of the work area; (3) glare experienced by drive-by motorists next to the construction zone; (4) glare experienced by workers; and (5) light trespass (El-Rayes et al. 2003). DOT officials in various states classified glare for road users as the number one lighting problem while contractors classified glare for workers as their most serious problem (El-Rayes et al. 2003). In order to control lighting problems in nighttime work zones, advanced lighting equipment and supplemental hardware can be used to minimize or mitigate the impact on construction workers and the traveling public in the work zone (El-Rayes et al. 2007). New lighting technologies such as balloon lights are now available to help control glare and other nighttime lighting problems (El-Rayes et al. 2007).

2.8 MERGE TECHNIQUES AND QUEUE DETECTION SYSTEMS IN WORK ZONES

For work zones that require lane closures, drivers need to be advised by advance lane closure signs placed on both sides of the roadway ½ mile in advance of the taper (MUTCD 2003). Additionally, lane reduction symbol signs are placed on both sides of the roadway, and a flashing arrow panel is usually placed at the beginning of the taper. This temporary traffic control (TTC) plan works well during most hours of the day when traffic demand is less than the capacity of the open lane. However, when the demand surpasses the open lane capacity, congestion develops and problems occur (Yulong and Leilei 2007). When the congestion extends upstream beyond the advance lane closure signs, the potential for rear-end work zone accidents increases (McCoy and Pesti 2008). To deal with this safety problem, several alternative lane merge strategies have been developed in recent years to better control traffic at work zone lane closures. Two basic merging approaches have been considered by many state DOTs for directing drivers into the open lane: (1) early lane merge; and (2) late lane merge (McCoy and Pesti 2001). The early lane merge is designed so that it directs drivers to merge into the open lane sooner than the regular merge. The late lane is designed so that it directs drivers to remain in their lanes until they reach the merge point at the lane closure taper. Many research studies have investigated new lane merge strategies such as “smart” lane merge to determine the improvement of the safety and efficiency of the merging operations in advance of work zone lane closures (McCoy et. al 2001; Beacher et al. 2004). The "smart" lane merge is a merging strategy that is capable of detecting congestion and providing real-time advisory information to motorists directing them to divert to an alternate lane or different route.

Recent advances in the use of Intelligent Transportation Systems (ITS) and their applications in temporary work zones are providing new tools that can be used for developing smart lane merge that can effectively manage queue congestions in and around work zones. New innovative and smart queue detection systems include: (1) adaptive queue warning devices (Wiles et al. 2003); and (2) dynamic message signs that are trailer mounted or portable. The adaptive queue warning system is a distributed, queue-warning system that can automatically adapt to the current traffic-flow situation within and upstream of the work zone that is equipped with an inexpensive but accurate speed sensor, a simple and adjustable signaling system, and necessary equipment for communication to a central controller (Sullivan et al. 2005). A recent study of ITS devices implementation in highway work zones showed that drivers found the adaptive systems more helpful than static road signs, which could subsequently increase their alertness and reduce work zone rear-end collisions (Sullivan et al. 2005). Dynamic warning message signs (DMS) are traffic control devices consisting of sensors that are activated when hazardous roadway, environmental, or operational conditions are detected by the sensors (Pesti et al. 2007). These signs can be used as an end-of-queue warning device that warns motorists against work zone hazards (Sisiopiku and Elliott 2005).

Computer simulation programs can also be used to determine the freeway work zone capacity and to estimate the motorists' queue delays associated with TMP alternatives (Jiang and Adeli 2004). Motorists' delay costs may be very expensive which may exceed the maintenance expenditures by responsible highway agencies (Chien and Schonfeld 2001). Computer models such as QUEWZ (Queue and User Cost Evaluation of Work Zones), and Quick Zone are being used to assist highway agencies create effective TMPs by estimating the impact of work zones queue lengths and associated travelers' delay. QUEWZ can be used to estimate travelers' queues based on empirical speed-flow-density relationships. Quick Zone is based on deterministic queuing models that estimate the hourly delay considering the time of the day and season variation (Karim and Adeli 2003). However, most of these computer models estimate the travelers' queues independent of the work zone characteristics such as work zone layout, work zone intensity, and work zone capacity (Adeli and Jiang 2003). Jiang and Adeli (2004) developed a computer model for freeway work zone capacity and queue delay and length estimation where it considered work zone characteristics such as: (1) percentage of trucks; (2) pavement grade; (3) number of lanes and closed lanes; (4) lane width; (5) work zone layout and intensity; (6) work zone speed, duration, time, and day; and (7) weather, pavement, and driver conditions.

2.9 FEDERAL RULES OF WORK ZONE SAFETY AND MOBILITY

Work zone safety continues to be a priority and major concern for the Federal Highway Administration (FHWA) as well as all state Departments of Transportations (DOTs) (FHWA 2009b; IDOT 2007). The FHWA is actively improving work zone safety and mobility through new regulations, better engineering, education, enforcement, and communication with concerned public safety agencies (FHWA 2009b). On September 9, 2004 the FHWA updated the work zone regulations at 23 CFR 630 Subpart J under the “Work Zone Safety and Mobility Rule” that affect all state projects as well as federal aid funded local highway projects starting on October 12, 2007 (Scriba et al. 2005). The main goal of the updated Rule is to reduce work zone crashes and congestion at three main implementation levels: (1) policy-level by developing general work zone policies that suit state transportation agencies; (2) process-level by developing agency’s work zone processes and procedures; and (3) project-level by identifying significant project requirements and developing appropriate transportation management plans (TMPs) to manage these requirements (Scriba et al. 2005). For each of these three implementation levels, the Rule includes provisions and guidance intended to assist transportation agencies in addressing work zone considerations starting early in planning, and progressing through project design, implementation, and performance assessment (FHWA 2009b).

The FHWA has also developed the National Highway Work Zone Safety Program (NHWZSP) to reduce fatal and injury crashes in work zones in order to enhance traffic mobility and safety within work zones (FHWA 2009a). To accomplish this, the program is designed to review the standards of traffic control devices, operational features, traffic control plans, and contract specifications to identify and improve work zone management practices. The program consists of four main components: (1) standardization; (2) compliance; (3) evaluation; and (4) implementation (FHWA 2009a). The National Work Zone Safety Information Clearinghouse (NWZSIC) can also be used to retrieve and analyze data on work zone crashes, statistics, laws and regulations, news and events, research, safety products, standards and practices, and training programs (FHWA 2009a). The following section highlights a collection of work zone policies adopted by five state DOTs to comply with the federal work zone and mobility rule.

2.10 STATE DEPARTMENTS OF TRANSPORTATION WORK ZONE RULES

Several state DOTs have developed special policies to comply with the federal work zone safety and mobility rule. This section provides a brief review for a number of basic features of the existing policies that are currently adopted by five states: (1) Illinois; (2) Texas; (3) Florida; (4) California; and (5) Ohio.

2.10.1 Illinois

The Illinois Department of Transportation (IDOT) bureau of design and environment publishes and maintains a manual which establishes uniform policies and procedures for the location, design and environmental evaluation of highway construction projects on the state highway system (IDOT 2002). The Illinois Comprehensive Highway Safety Plan (ICHSP 2005) has identified work zone safety as a priority area and it seeks to provide a high level of safety for both motorists and construction workers. The plan outlines the Illinois Department of Transportation (IDOT) guidelines to comply with the FHWA Work Zone Safety and Mobility Rule. The three main safety goals of this plan are to: (1) achieve zero worker fatalities for traffic-related work zone crashes; (2) reduce the number of motorist fatalities in traffic-related work zone crashes by 10% each year; and (3) reduce the number of work zone crashes by 5% from each prior year (ICHSP 2005).

In order to implement the ICHSP, IDOT has developed: (1) significant route location maps; and (2) work zone safety and mobility process flow charts, as shown in Figure 2.1 (ICHSP 2005). First, the work zone significance is determined using the significant route location maps that classifies routes into three categories: (1) non-significant; (2) significant – short term (less than 3 days); and (3) significant – long term. The work zone safety and mobility process flow chart is then used to guide the necessary steps to implement the federal work zone safety and mobility rule, as shown in Figure 2.4.

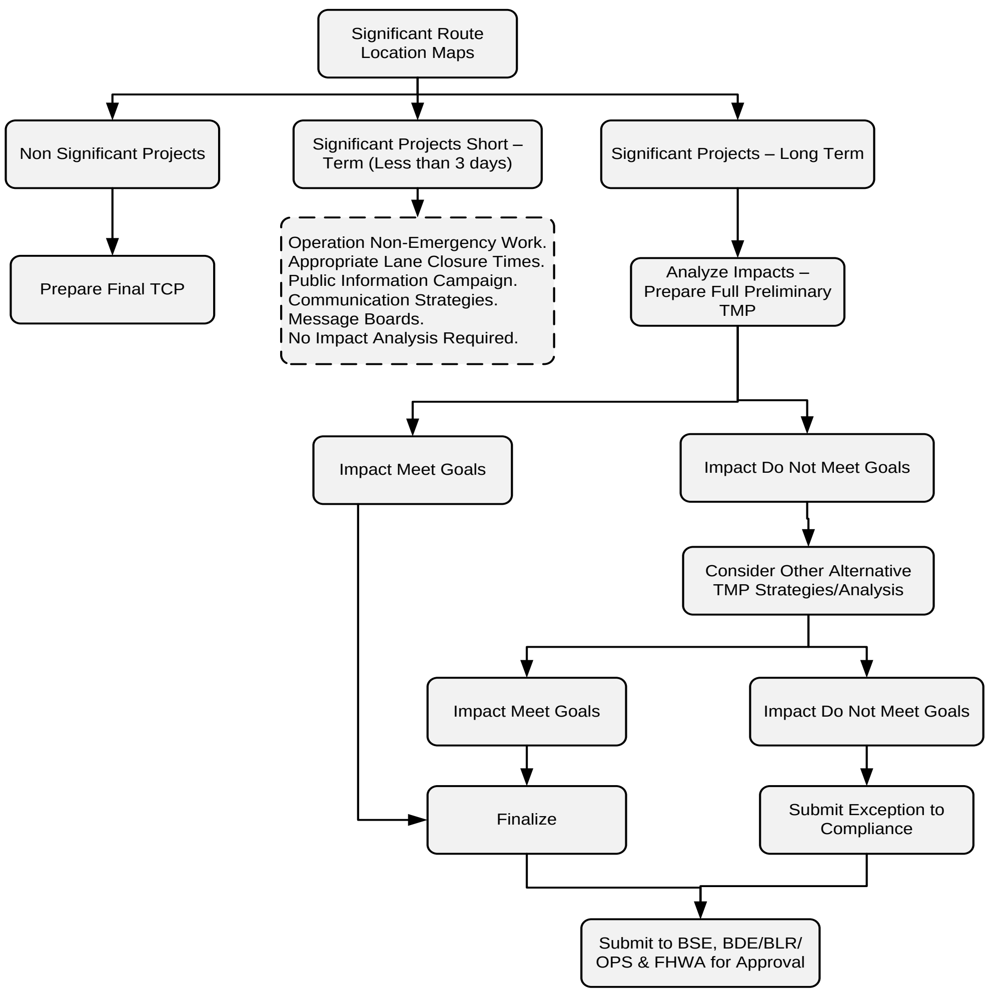


Figure 2.4 Work zone safety and mobility process-flow chart (ICHSP 2005).

For significant long-term projects, impact analysis is required to determine the greater impact that work zones may cause to traffic (FHWA 2009b). The impact analysis should involve the safety and mobility impacts of the construction/maintenance project utilizing hourly volume maps, district knowledge and experience, site reviews, computer simulation programs such as QUEWZ, TSIS-CORSIM, and Quick zone (IDOT 2007). To address the expected impacts, various Transportation Management Plans (TMP) strategies are developed and the resulting impacts of delays and queuing are evaluated.

The ICHSP (2005) also seeks to assess and improve the safety of work zones by requiring the submission of a detailed work zone crash summary report for any fatal work zone crash within 10 days to the Bureau of Safety Engineering. This report analyzes the crash and includes the following information: (1) summary of the type of construction; (2) description of the traffic control in place at the time of crash; (3) description of the traffic conditions at the time of the crash; (4) description of the contractor's operations at the time of the crash; (5) description of the weather conditions; (6) pavement conditions, and time of day; (7) description of changes made to the traffic control as a result of the crash; (8) recommendations for change to IDOT standards, and (9) photos of the traffic control throughout the project before and after the crash (ICHSP 2005).

2.10.2 Texas

The Texas Department of Transportation (TxDOT) developed a project development process manual for work zones that includes details of major steps involved in a transportation project starting from the phase of identifying project needs through the construction and implementation phase (TxDOT 2009). The manual provides guidance on the use of accelerated construction strategies to expedite project plan delivery and construction completion. In order to achieve this acceleration goal, contractors and designers are required to perform a thorough analysis for the construction time using new contracting strategies that emphasize timely completion (TxDOT 2009).

2.10.3. Florida

The Florida Department of Transportation (FDOT) provides procedures, training and awareness activities that foster safe work practices and workplaces for road projects on interstate highways for both motorists and construction workers as well (FDOT 2009). One of the distinctive features of the FDOT is that it employs a lane closure policy for roadway projects on interstate highways that the work zone design plans should maintain the existing number of lanes for the various work phases (FHWA 2009b). This means that no lane closures strategies are permitted on any interstate construction work zone where only two travel lanes exist. The implementation of such policy resulted in reduced driver delay and frustration and therefore better public relations (FHWA 2009b).

2.10.4 California

The California Department of Transportation (Caltrans) uses a standard specification manual that contains several chapters including: general provisions, miscellaneous, grading, subbases and bases, surfacing and pavements, structures, drainage facilities, right of way and traffic control facilities and materials (FHWA 2009b). The miscellaneous chapter contains traffic-related work zone provisions that list temporary traffic control devices such as: barricades, flashing arrow signs, portable delineators, portable flashing beacons, and construction area signs. The Caltrans standards require that all temporary traffic control devices conform to the MUTCD provisions and the MUTCD California Supplement (Caltrans 2006). Caltrans has also developed specific criteria for identifying significant projects based on traffic impact when it is 30 minutes above normal recurring traffic delay on the existing facility or above the delay limit set by the district resident traffic engineer (Scriba et al. 2005).

2.10.5 Ohio

The Ohio Department of Transportation (ODOT) utilizes the Ohio Manual of Uniform Traffic Control Devices (OMUTCD) which includes a description of the standard traffic control devices used in work areas and traffic incident management areas, guidelines for the application of the devices, and typical application diagrams (ODOT 2003). The ODOT manual lists eight major traffic control considerations that impact any transportation management plan of a work zone: (1) time; (2) location; (3) type; (4) speed; (5) traffic volume; (6) nature of traffic; (7) law enforcement agencies; and (8) temporary traffic control signs.

2.11 REPORTING OF WORK ZONE CRASHES

Work zones create conflicts between construction activities and traffic which often cause hazardous conditions for motorists and construction workers resulting in high number of crashes. Work zone crashes are defined as crashes that occur in the terrain of a work zone whether it is a construction, maintenance, or utility work zone including any crashes that occur within an area marked by signs, barricades, or other work zone signs (MUTCD 2003). A number of research studies were conducted to investigate the characteristics of work zone crashes in many states (Daniel et al. 2000; Garber and Zhao 2002; Harb et al. 2008; Mohan and Zech 2005). This section summarizes the findings of six major studies that analyzed work zone crashes in six states: (1) Florida; (2) Kansas; (3) Georgia; (4) Virginia; (5) Illinois; and (6) New York, as shown in Table 2.5-A and Table 2.5-B.

Table 2.5-A List of Work Zone Crash Research Studies

<table>
<tr><th>N.</th><th>Researcher(s)</th><th>Study Subject</th><th colspan="2">Crash Classification
(Category and Variables)</th><th>Contributing Factors
(Category and Variables)</th><th>State</th></tr>
<tr><td rowspan="3">1</td><td rowspan="3">Raub et al. (2001)</td><td rowspan="3">Traffic Control Systems in Construction Work Zones</td><td>Crash Severity</td><td>• Fatal
• Injury
• Property Damage Only (PDO)</td><td rowspan="3">Time Information: Time, Day
Climatic Environment: Light, Weather, Surface
Driver Condition: Vision
Vehicle Type: Passenger car, Pickup
Crash Events: At-fault Driver Action</td><td rowspan="3">Illinois</td></tr>
<tr><td>Number of Vehicles</td><td>• Single-Vehicle
• Multi-Vehicle</td></tr>
<tr><td>Collision Manner</td><td>• Rear end
• Fixed object in road
• Angle
• Sideswipe</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">Harb et al. (2008)</td><td rowspan="2">Freeway Work-Zone Crash Analysis and Risk Identification Using Multiple and Conditional Logistic Regression</td><td>Work Zone</td><td>• Work Zone
• Nonwork Zone</td><td rowspan="2">• Driver: Age, Gender Driving under the influence, residence code
• Vehicle: Speed, Vehicle speed
• Environment: Speed limit, Road surface condition, Rural/Urban, Road Characteristics, Event Location, Weather, Lighting Condition, No. of lanes</td><td rowspan="2">Florida</td></tr>
<tr><td>Number of Vehicles</td><td>• Single-Vehicle
• Multi-Vehicle</td></tr>
<tr><td>3</td><td>Bai and Li (2006)
Li and Bai (2008)</td><td>Comparison of Characteristics between Fatal and Injury Crashes in Highway Construction Zones</td><td>Crash Information</td><td>• Vehicle Maneuver
• Crash Severity
• Crash Type
• Vehicle Type
• No. of Vehicles</td><td>• Driver: Age, Gender
• Time Information: Time, Day, Month, Year
• Climatic Environment: Light, Weather, Surface
• Road: Class, Character, No. lanes, Speed, Crash location, TCD, Terrain,
• Human: Alcohol, Fall asleep, Follow too close, Failed to yield</td><td>Kansas</td></tr>
</table>

Table 2.5-B List of Work Zone Crash Research Studies

N.	Researcher(s)	Study Subject	Crash Classification (Category and Variables)		Contributing Factors (Category and Variables)	State
4	Garber and Zhao (2002)	Distribution and Characteristics of Crashes at Different Work Zone Locations in Virginia	Crash Severity	• Fatal • Injury • Property Damage Only (PDO)	**Highway Type:** Urban Interstate Rural Interstate Urban Primary Rural Primary	Virginia
			Collision Manner	• Rear end • Fixed object in road • Angle • Sideswipe • Fixed Object off the road		
			Work Zone Area	• Advance Warning • Transition • Longitudinal Buffer • Activity • Termination		
4	Daniel et al. (2000)	Analysis of Fatal Crashes in Georgia Work Zones	Work Zone	• Work Zone • Nonwork Zone	**Roadway Functional Classification:** Rural Principal Arterial – Interstate Rural Principal Arterial – Other Rural Minor Arterial Rural Major Collector Urban Principal Arterial – Interstate **Roadway Characteristics:** Profile, Alignment **Other:** Truck percentage, Lighting conditions	Georgia
			Work Zone Activity	• Idle Work Zone • Active Work Zone		
			Collision Manner	• Rear end • Angle • Sideswipe • Other		
6	Mohan and Zech (2005)	Characteristics of Worker Accidents on NYSDOT Construction Projects	Crash Severity	• Fatal • Severe Injury	**Traffic-related accidents**: Work space intrusion, worker struck-by vehicle inside work space, flagger struck-by vehicle, worker struck by vehicle entering/exiting work space, construction equipment struck-by vehicle inside work space.	New York

2.11.1 Illinois

Raub et al. (2001) studied 7,749 work zone crashes in 1994 and 6,206 crashes in 1995 that the State of Illinois coded as work zone crashes. The analysis examined similarities and differences in crashes between these two years, and between work zone and nonwork zone crashes to identify the work zone contributing factors. The main findings of this study included: (1) rear-end crashes were the most common type of collision for vehicles within work zones and involved more than two vehicles; (2) the main contributing human factor was "too fast for conditions"; (3) work zone crashes were more likely to result in an injury; (4) 83% of work zone crashes occurred in clear weather and 70% during the daylight hours where the road was dry; and (5) most of the vehicles involved in work zone crashes were passenger vehicles. Moreover, the report compared the crash data in Illinois to seven other states and showed that Illinois had more rear-end collisions, more angle collisions, and fewer crashes that were related to sideswipes and fixed objects. The study reported that the discrepancy of police crash reports covering work zone characteristics negatively affected the accuracy of the study results.

2.11.2 Florida

One of the recent studies was conducted by Harb et al. (2008) which focused on the analysis of work zone crashes in the State of Florida. The objective of this study was to conduct a statistical analysis to study the impact of a number of factors on work zone crashes, including driver-related factors, types of vehicles, and work zone features. The authors employed the Florida Crash Records Database for years 2002, 2003, and 2004 for their study. The study evaluated freeway single-vehicle and two-vehicle crashes in work zones. For the single-vehicle crash analysis, the most influencing contributing factors were (1) vehicle type (passenger car, SUV); (2) truck and large truck involvement; (3) roadway geometry (straight, upgrade/downgrade); and (4) lighting conditions. As for the multi-vehicle crashes analysis, the most influencing contributing factors were (1) driver's age, gender, and resident code; (2) driving under the influence of narcotics/alcohol; and (3) geometry and lighting conditions.

2.11.3 Kansas

The characteristics of fatal and injury accidents in Kansas construction zones were investigated by Bai and Li (2006). The authors of this study analyzed 157 fatal crashes that occurred in the State of Kansas between 1992 and 2004. The crash data were collected from the Kansas DOT accident database and combined with the original accident reports. The Kansas DOT's database was used to identify the responsible drivers/vehicles for each fatal crash studied then the original accident report was used for adding detailed crash descriptions. The crash frequency distribution resulted in the following main findings: (1) inattentive driving and misjudgment/disregarded traffic controls were the two most frequent human errors for all age groups under varying light conditions; (2) work zones on two-lane highways in rural areas had the highest fatal crash frequencies; and (3) most single-vehicle crashes occurred during nighttime.

In another study performed by Li and Bai (2008) to determine if there were any potential characteristic differences between fatal and injury crashes in Kansas, five main characteristics were studied: drivers at fault, crash time, location, type, and causal factors. The comparative analysis resulted in the following: (1) rear-end was the dominant type of injury crashes, head-on was the dominant type of fatal crashes; (2) the majority of the injury crashes occurred on straight and level highways when light conditions were favorable; and (3) the majority of fatal crashes occurred in complicated road geometrics when unfavorable light conditions existed.

2.11.4 Virginia

A clear understanding of work zone crash characteristics helps identify appropriate countermeasures to reduce work zone hazards. Garber and Zhao (2002) investigated the characteristics of 1,484 work zone crashes that occurred in the State of Virginia from 1996 through 1999. The main findings of this study included: (1) the activity area was the most prevalent crash location in a work zone (70%); (2) property damage only (PDO) was the most prevalent severity type; and (3) rear-end crashes were the predominant collision type.

2.11.5 Georgia

Fatal crashes occur most frequently in construction work zones rather than maintenance work zones. Daniel et al. (2000) examined the difference between fatal crash activity within work zones compared with fatal crashes in nonwork zone locations. The analysis utilized the data of a previous study performed by Georgia DOT that identified the manner of collision, location, and construction activity associated with fatal crashes in work zones. In addition, the research study investigated the influence of work zone activity on the frequency of fatal crashes. The main conclusions of this study included:

- Work activity had no impact on work zone crashes.
- High proportions of work zone crashes were rear-end crashes.
- Percentage of trucks was a significant contributing factor.
- Most work zone crashes occurred on rural principal roadways.

- Roadway geometry did not influence fatal crashes in work zones.
- The primary human factors of work zone crashes were driver lost control, failed to yield, and too fast for conditions.
- Fatal crashes were correlated with lighting conditions

2.11.6 New York

Mohan and Zech (2005) studied worker accidents in New York State Department of Transportation (NYSDOT) construction projects. The goal of their study was to provide cost-effective safety measures to protect construction workers in highway work zones. The study analyzed work zone crashes involving 36 fatalities and 3,055 severe injuries to construction workers from 1990 to 2001 in the State of New York and classified work zone crashes into two major types: construction work area accidents and traffic crashes involving construction workers. The detailed analysis of the traffic related crashes revealed that work space intrusions are the most fatal crash type representing 35.7% of all fatal traffic crashes involving construction workers. The study recommended the highway authorities and contractors invest more in worker protection to reduce the number of traffic-related crashes involving construction workers.

2.12 ANALYSIS OF WORK ZONE CRASH

This section presents a brief discussion of three statistical methods that have been applied in previous studies to analyze work zone crashes in order to identify their contributing factors. These utilized statistical methods are: (1) multiple and conditional logistic regression; (2) binary logistic regression; and (3) proportionality tests.

2.12.1 Multiple Logistic Regression

Logistic regression is an alternative method to classical regression techniques which can be applied to a large family of parametric distributions, involving both discrete and continuous variables (Harb et al. 2008). Logistic regression can be classified as multiple logistic regression and binary logistic regression. Harb et al. (2008) used multiple logistic regression along with stratified sampling to analyze work zone freeway crash characteristics. The State of Florida crash database during the years 2002 to 2004 was used for this study. The main objective of this study was to identify the characteristics and risk factors (driver, environment, and vehicles) that impact single- and multiple-vehicle crashes on highway work zones. The multiple logistic regression analysis was used to model and compare work zone versus non-work zone crashes for (1) single-vehicle crashes; and (2) two-vehicle at-fault drivers crashes. The SAS procedure "LOGISTIC" was used for developing the model and fourteen variables were identified using the relative accident involvement ratios (RAIR) as follow:

$$RAIR_i = \frac{\frac{D1i}{\sum D1i}}{\frac{D2i}{\sum D2i}} \tag{2.1}$$

Where,

$RAIR_i$ = relative accident involvement ratio for type i drivers/vehicles/environment;

$D1i$ = number of at-fault drivers of type i in work zone crashes; and

$D2i$ = number of at-fault drivers in non-work zone crashes.

2.12.2 Binary Logistic Regression

Binary logistic regression analysis is a statistical technique for describing the relationships between a set of independent explanatory variables and a response variable or outcome (Bai and Li 2006). The regression technique is a suitable method for analyzing traffic crashes that involve establishing a relationship between the occurrence of a crash and various contributing factors. Bai and Li (2006) applied binary logistic regression analysis to investigate the characteristics of fatal crashes in the State of Kansas. The regression analysis was used to quantify the effectiveness of two commonly used work zone traffic control devices, namely flagger and stop sign. The logistic models for utilizing the flagger and stop sign are shown in Equations (4.2) and (4.3), respectively. The outcome of this study revealed that (1) the presence of flagger control in work zones can reduce the probability of male drivers causing fatal crashes by 15%; and (2) the use of stop signs can reduce multi-vehicle fatal crashes and lowered conditional probability of fatal crashes involving multiple vehicles by 13%.

$$logit\{Y = 0\backslash X\} = 1.86 - 0.91X \tag{2.2}$$

$$logit\{Y = 0\backslash X\} = 1.33 - 0.68X \tag{2.3}$$

Where,

The response variable Y was assigned with binary values 0 and 1 to denote single-vehicle crashes and multi-vehicle crashes, respectively. The explanatory variable X is the presence of a flagger or stop sign/signal (1 for presence and 0 for no presence).

2.12.3 Proportionality Tests

Garber and Zhao (2002) analyzed work zone crashes that occurred in the State of Virginia from 1996 through 1999 using proportionality tests. Percentage distributions were determined for each crash based on the crash locations, crash severities, and collision types. Proportionality tests were performed to determine the significance of these distributions using the test statistic “Z value” which is calculated as shown in Equations (4.4) to (4.7).

$$Z = \frac{P1-P2}{\sqrt{P(1-P)}\left[\left(\frac{1}{n1}\right)+\left(\frac{1}{n2}\right)\right]} \quad (2.4)$$

$$P1 \quad = \frac{Y1}{n1} \quad (2.5)$$

$$P2 \quad = \frac{Y2}{n2} \quad (2.6)$$

$$P \quad = \frac{Y1+Y2}{n1+n2} \quad (2.7)$$

Where,

P1, P2 = two proportions to be compared;

P = pooled estimate;

n1, n2 = population sample sizes;

Y1, Y2 = number of successes for populations 1 and 2. The null hypothesis $\mathrm{H0}$: P1 = P2 was tested against that of $\mathrm{H1}$: P1 > P2. The null hypothesis was rejected and $\mathrm{H1}$ was accepted if the calculated Z statistic > Z (at 5% significance level).

The aforementioned research studies of work zone crashes examined fatal, injury, and property damage crashes to identify factors contributing to unsafe conditions caused by work zones. The most frequently cited contributing factors of work zone crashes based on previous research studies are summarized in Table 2.6.

Table 2.6 Crash Classification and Contributing Factors for Work Zones

Crash Classification		Contributing Factors	
Category	**Variables**	**Category**	**Variables**
Work Zone	Work Zone	**Driver**	Age
	Nonwork Zone		Gender
Driver's Fault	At-Fault Driver		Driving under the influence
	Not At-Fault Driver		Residence Code
Number of Vehicles	Single-Vehicle	**Vehicle**	Speed
	Multi-Vehicle		Vehicle Type
Collision Manner	Head-On	**Environment**	Event location
	Rear-End		Weather
	Fixed Object		Lighting Condition
	Angle		Number of lanes
	Side-Swipe	**Roadway**	Road surface condition
Crash Severity	Fatal		Rural/urban
	Injury		Road Profile/Alignment
	PDO		Road Class, Character
Work Zone Area	Advance Warning		Number of Lanes
	Transition		Speed Limit
	Longitudinal Buffer		Crash Location
	Activity		Surface Type
	Termination	**Timeline**	Time, Day, Year
		Traffic control	Traffic control Devices
			Traffic Control Plan
			Work Zone layout

2.13 ANALYSIS OF ROADWAY CRASHES

Many studies have been performed in the past few decades to investigate the effects of various highway designs on safety. The investigated highway design elements included: cross section design, horizontal alignment, vertical alignment, roadside features, and pavement conditions (Hadi et al. 1995). Previous studies indicated that improvements to these design elements could produce significant reduction in the number of crashes (Bonneson et al. 2006; Harwood et al. 2000; Hong et al. 2005). Many research studies quantified the effect of highway design elements on total crash rates for various types of roadway using accident prediction models (Krammes and Hayden 2003). Several statistical methods were applied to develop these accident prediction models. The generalized linear modeling and the tree-based regression are two types of these statistical methods and are explained in the following sections.

2.13.1 Generalized Linear Modeling

The Generalized Linear Modeling is an extension of the linear modeling process that allows models to be fit to data that follow probability distributions such as Poisson and Binomial distributions (McCullagh and Nelder 1989). A number of models for predicting highway crashes were developed using generalized linear modeling, including three that were based on crash datasets from: (1) California; (2) Texas; and (3) Canada.

1- California

Jonsson et al. (2007) studied roadway crashes by modeling different types of crashes and intersections on rural four-lane highways in the State of California. Four different types of crashes were studied: opposite-direction, same-direction, intersecting-direction, and single-vehicle crashes. Two types of intersections were also studied: T-intersection, and four-leg intersection. Data were collected from the Highway Safety Information System (HSIS) regarding intersection design, traffic volumes, number of accidents, and the vehicles involved. The different models for predicting the number of crashes per crash type were developed using generalized linear modeling and the GENMOD procedure in the statistical software SAS with the assumption that the number of crashes followed a negative binomial distribution (SAS 2004). Three different models were developed for each type of crash and intersection: (1) basic model where the annual average daily traffic (AADT) was the only single variable considered; (2)

multi-variable model that included all significant variables except the AADT, and (3) full model with all variables including the AADT. The authors used 2 forms for each of the three models as shown in Equations (4.8) and (4.9). The development of the multi-variable models was performed by adding one variable at a time and choosing the variable that performed the best. The study results showed that (1) terrain variable was found to be a good predictor variable for single-vehicle crashes; (2) single-vehicle crashes had a practically linear relationship with the total number of entering vehicles in the intersection; and (3) opposite- and same-direction crashes mostly are related to major traffic flow.

$$N_{Acc} = AADT_{major}^{\beta 1} \times \ AADT_{minor}^{\beta 2} \times e^{\beta 0+ \beta 3 \times x3+ \beta 4 \times x4+\cdots \ldots\ldots\ldots+ \beta n \times xn} \tag{2.8}$$

$$N_{Acc} = \left(AADT_{major} + \ AADT_{minor}\right)^{\beta 1} \times \ e^{\beta 0+ \beta 2 \times x2+ \beta 3 \times x3+\cdots \ldots\ldots\ldots+ \beta n \times xn} \tag{2.9}$$

Where,

N_{Acc} = predicted number of crashes per year and intersections,

$AADT_{major}$ = traffic flow on major road,

$AADT_{minor}$ = traffic flow on minor road,

β_i = model parameters, and

x_i = variables describing intersections.

2- Texas

Bonneson and Zimmerman (2007) described a procedure for using accident modification factors in the highway design process to evaluate the safety benefits associated with alternative geometric designs. This procedure consisted of six steps and should be repeated for each design alternative being considered to determine the safety outcome benefit of each alternative. The six steps are: (1) identify roadway section; (2) divide section into separate facility elements; (3) gather data for subject element; (4) compute expected crash frequency; (5) repeat steps 3 & 4 for all roadway sections; and (6) cumulate all results for roadway section. The crash data for 567 roadway segments were analyzed and the Generalized Modeling procedure (GENMOD) in SAS was used to automate the regression analysis (SAS 2004). The analysis resulted in a number of crash prediction models for different road types. The expected crash frequency was computed using a safety prediction model that consisted of a base model adjusted using various accident modification factors (AMFs) to tailor the resulting estimate to a specific highway segment. The basic form of the safety prediction model was given in Equations (4.10) and (4.11).

$$E[N] = E[N]_b \times AMF_1 \times AMF_2 \ldots\ldots\ldots\ldots\ldots \times AMF_n \tag{2.10}$$

$$AMF = 1 - CRF \quad (CRF\text{: crash reduction factor}) \tag{2.11}$$

Where,

$E[N]$ = expected crash frequency in crashes/year,

$E[N]_b$ = expected base crash frequency in crashes/yr,

AMF_i = accident modification factor for geometry or traffic control variable i

The expected base crash frequency model $E[N]_b$ depends on traffic volume and segment length L, as shown in Equation (4.12) for frontage roads (Bonneson et al. 2007). The accident modification factor (AMF) for frontage roads depends on the average lane width, as shown in Equation (4.13).

$$E[N]_b = 0.00134\, ADT^{0.641}\, L \tag{2.12}$$

$$AMF_{LW} = e^{-0.188(Wl-12.0)} \tag{2.13}$$

AMF_{LW} = lane width accident modification factor,

Wl = average lane width

3- Canada

Sawalha and Sayed (2001) developed an accident prediction model for estimating the safety performance of urban arterial roadways in the Greater Vancouver Regional District in British Columbia, Canada. The traffic- and road-related variables included in their analysis were: section length, traffic volume, unsignalized intersection density, driveway density, pedestrian crosswalk density, number of traffic lanes, type of median, and type of land use. The study made use of sample accident, traffic volume, and geometric data representing 58 arterials in the cities of Vancouver and Richmond, B.C through the years 1994–1996. Geometric data representing the previous variables were directly collected from the field. The generalized linear modeling approach (GLIM) was used for data analysis and led to the development of the accident frequency model shown in Equation (4.14).

$$E(\Delta) = e_0 \times L^{a_1} \times V^{a_2} \times \exp \sum_{j=1}^{m} b_j x_j \qquad (2.14)$$

Where,

$E(\Delta)$ = predicted accident frequency,

L = segment length,

V = segment annual average daily traffic

x_j = any of m variables additional to L and V,

$a_0, a_{1,} a_2, b_j$ = model parameters

The estimation of the model parameters was performed using GLIM, and the error structure was calculated by applying both the Poisson and negative binomial error structures. The basic model expressed the relationship between accident occurrence and the two exposure factors (segment length and AADT). The rest of the variables were added to the basic model one by one in a forward procedure then outlier analysis was performed for the initial model.

2.13.2 Tree-based Regression

Hierarchical Tree-Based Regression (HTBR) methodology is a statistical method that can be applied to generate logical models for a number of data sets. The methodology is used for predicting highway crashes by simulating the dataset into a tree-based diagram where the tree starts with one parent node that can split into exactly two child nodes, and each node can split to zero, one, or two more child nodes. Nodes are specified on the basis of the deviance of the sample, and the splitting value is chosen so that the deviance in each of the two child nodes is minimized. HTBR proves to be more effective in handling missing information by treating a missing independent value as a valid response instead of ignoring the entire observation which means it can overcome one of the significant challenges of crash analysis.

Abdel-Aty et al. (2005) studied the different factors that affect signalized intersection crashes by type of collision. The study explored the hypothesis that different types of collisions are affected by different independent variables. Several databases of different counties in the State of Florida were used to ensure the completeness of the data that included information collected from crashes that were reported on long and short forms. The authors of this study adopted the HTBR for their analysis to predict the expected number of crashes reported on both long and short forms for eight different collision types. HTBR nodes deviance was defined as shown in Equation (4.15). The analysis was performed using SAS, where stepwise variable selection and splitting criterion were based on an F-test. The study results showed that (1) the traffic volume along the major roadway was the most important contributing factor only for predicting right-turn crashes in the restricted data set; and (2) speed limit, number of lanes on minor road, and exclusive left turn lanes on minor roads were the most important among other dependent and independent variables.

$$D = \sum_{i=1}^{L}(Y_{ia} - X_a)^2 \qquad (2.15)$$

Where,

D = deviance (the sum of squared error) of y at node a,

Y_{ia} = observation at node a,

X_a = average of L observations in node a

CHAPTER 3

DATA COLLECTION AND FUSION

3.1 INTRODUCTION

The objective of this chapter is to present the crash data sources used in the analysis of work zone crashes and the utilized methodology for extracting work zone injury and fatal crashes. Crash data sources include: (1) National Highway and Traffic Safety Administration (NHTSA) crash data; (2) Highway Safety Information System (HSIS) crash data; and (3) police crash reports. This chapter presents the utilized methodology for collecting and fusing work zone crash data from all these sources. The frequency and crash severity analysis of these fatal and injury work zone crashes are discussed in detail in Chapter 4.

3.2 ILLINOIS CRASH DATA COLLECTION

Work zone crashes are defined as crashes that occur in the terrain of a work zone whether it is a construction, maintenance, or utility work zone (MUTCD 2003). The first research task in the analysis of work zone crashes focuses on gathering available data and reports on work zone crashes in Illinois from all available resources to build a comprehensive dataset. This was accomplished by collecting the latest available data on work zone crashes in Illinois from all available resources, including: (1) the National Highway Traffic Safety Administration (NHTSA 2007); (2) the Highway Safety Information System (HSIS 2009); and (3) police crash reports for fatal work zone crashes.

3.2.1 National Highway Traffic Safety Administration (NHTSA) Data

The first source of data is the National Highway Traffic Safety Administration (NHTSA) crash data files for the state of Illinois that contain data on approximately 400,000 accidents per year. The original source of this data contains police reports in Illinois that document crash data in a standard format which contains data on the characteristics of the crash, the vehicles, and the people involved. These reports document accidents that involve personal injury or total property damage of $500 or more (NHTSA 2007). The data recorded in these reports are sent to the division of traffic safety where location codes from a series of maps are identified and assigned to each crash, and the basic accident data are coded into a central crash data file at the state level. This Illinois crash data is then sent annually to the National Highway Traffic Safety Administration (NHTSA) where various data formats are converted to Statistical Analysis System (SAS) data files (NHTSA 2007).

The latest available data from the NHTSA contained 62,197 work zone crashes that caused 320 fatalities and 25,718 serious injuries during a ten year period from 1996 to 2005, as shown in Table 3.1. The annual number of work zone crashes over the analyzed ten year period (1996-2005) is presented in Figure 3.1. It clearly shows an increasing trend reaching a peak in 2001 and then the annual number of work zone crashes slightly decreases and fluctuates over the following four years (2002 to 2005). The composition of Illinois work zone crashes for the years 1996-2005 is presented in Figure 3.2 that illustrates that the Property Damage Only (PDO) crashes represent more than 70% of the total number of crashes. The number of fatalities over this time period is also presented in Figure 3.3.

Table 3.1 Illinois Work Zone Crashes (1996-2005)

Year	No. of Fatal Crashes	No. of Fatalities	No. of Injury Crashes	No. of Injuries	No. of PDO Crashes	Total Crashes
1996	29	33	1278	1974	2292	3599
1997	33	38	1774	2643	3999	5806
1998	18	20	1603	2480	3437	5058
1999	15	17	1906	2786	4344	6265
2000	31	38	1822	2672	4963	6816
2001	31	36	2196	3043	5824	8051
2002	30	31	2023	2987	4919	6972
2003	31	44	1887	2794	5053	6971
2004	30	38	1514	2282	4470	6014
2005	22	25	1470	2057	5153	6645
Total	**270**	**320**	**17473**	**25718**	**44454**	**62197**

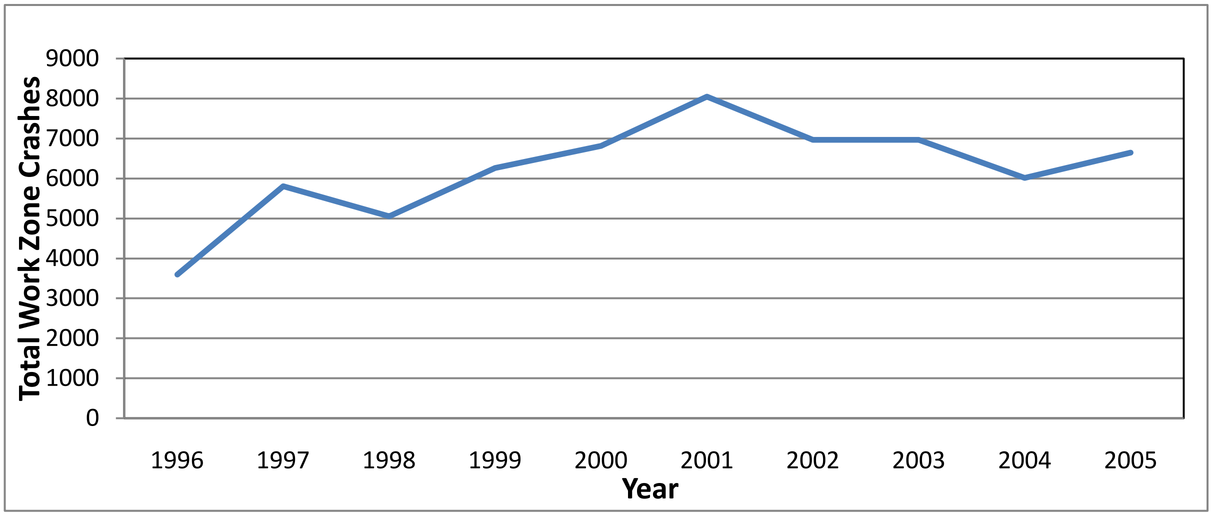


Figure 3.1 Illinois work zone crashes (1996-2005)

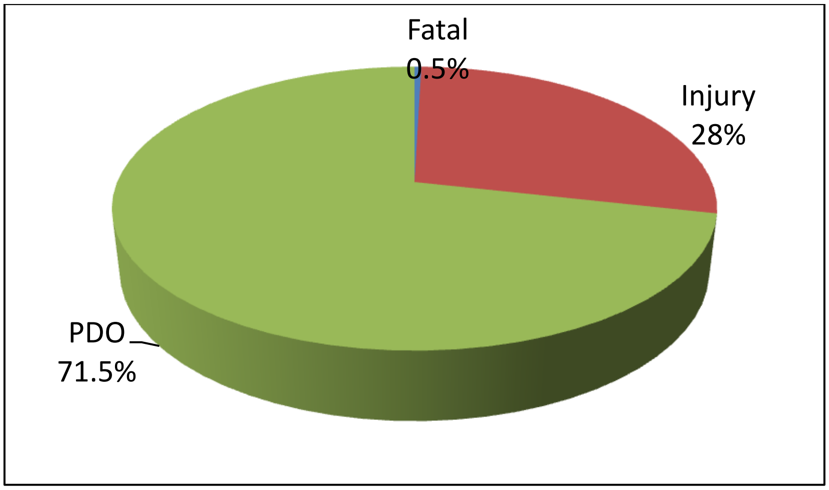


Figure 3.2 Overall work zone crash composition (1996-2005).

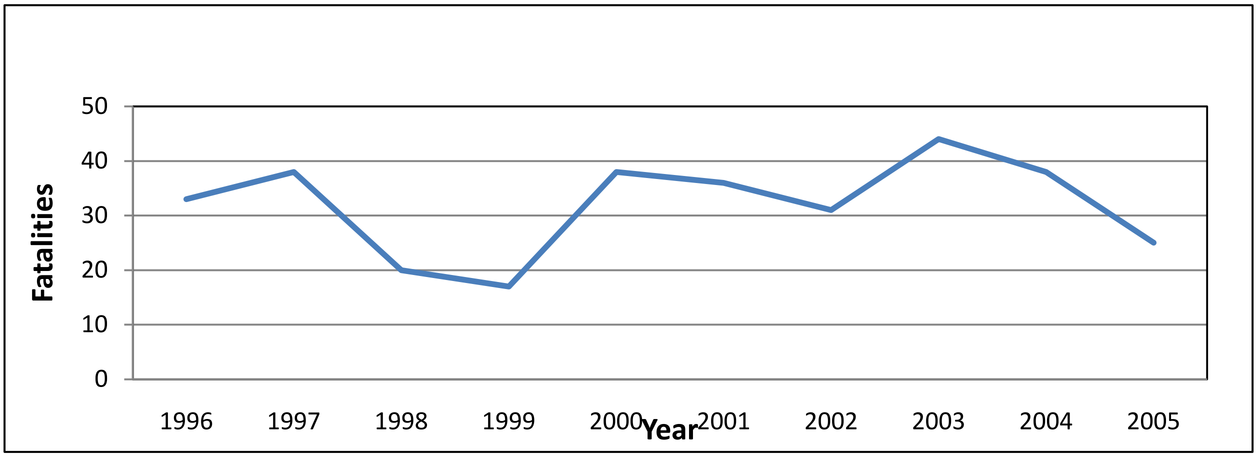


Figure 3.3 Illinois work zone fatalities (1996-2005).

3.2.2 Highway Safety Information System (HSIS) Data

The second source of data is this study is the Highway Safety Information System (HSIS) that contains only a subset of the aforementioned NHTSA crash data records as it includes between 105,000 and 205,000 crashes per year (www.hsisinfo.org). The main reason that the HSIS data was collected and analyzed in this study is the additional road and traffic data that it provides that are not available in the aforementioned NHTSA data files (Council and Mohamedshah 2009). The crash dataset provided by HSIS for the state of Illinois has, in addition to the aforementioned three NHTSA files, a fourth file (*Roadlog file*) that contains additional data on the road and traffic such as number of lanes, lane width, median type and width, AADT, commercial volume, and speed limit. The *Roadlog file* is merged with the *crash file* using both “Cntyrte: County Route” and “milepost” in the *crash file* and matched with “cnty_rte: County Route” and “begmp: Beginning milepost” in the *Roadlog file*.

3.2.3 Police Reports on Fatal Crashes

The third source of data in this study is Illinois police reports on fatal work zone crashes. These reports were collected from IDOT and were analyzed to identify and incorporate any additional information on the crash characteristics that are not available in the NHTSA and HSIS files.

3.3 ILLINOIS WORK ZONE CRASH DATA FUSION

Crash and road datasets from the aforementioned data sources need to be fused to enable a comprehensive analysis of work zone crashes in Illinois and their contributing factors. Data fusion was performed to compile all the relevant data of each work zone crash case into one single line in a spreadsheet without missing any key data. This data fusion was automatically performed using SAS 9.2 in two steps: (1) identifying all data on responsible vehicles and persons involved in the work zone crash and merging them with other relevant crash and road data from other files; and (2) identifying all changes and variations in data reporting over the years and transforming them to a unified pattern in the entire analysis period that covered data from 1996 to 2005. For example, the crash variable "Accident Severity" was used up to 2003 to indicate the most severe injury sustained by any occupant or non-occupant involved in the crash using numbers: 1, 2, and 3 to represent fatal, injury, and property damage, respectively. Since 2003, the reporting of this variable changed using the three letters F, I, and P to represent fatal, injury, and property damage, respectively. Similarly, other crash variables such as "Alignment" and "Visual Obstruction" were not included in years prior to 2004 and since then they are documented and reported in the data files. Whenever these variations in data reporting were encountered in the analyzed data set, IDOT officials and HSIS personnel were consulted to clarify and/or confirm these variations. The following sections present in more details the fusion of: (1) NHTSA crash data; and (2) HSIS crash data.

3.3.1 National Highway Traffic Safety Administration Crash Data Fusion

The data fusion in this Chapter utilized the most recent ten years (1996-2005) of crash records that were collected from the NHTSA for the state of Illinois. The released NHTSA data files for the state of Illinois contained more than 4,000,000 crash records for the ten year period, including 62,197 work zone crashes, as shown in Table 3.1. The Illinois crash dataset obtained from NHTSA was structured in three main files: (1) *crash file*; (2) *vehicle file*; and (3) *person file* (NHTSA 2007). The *crash file* contains data on the environment and roadway conditions at the time of the crash. A crash record in the *crash file* can be sorted and organized using the “Accident Number” variable which represents a unique identification number, and accordingly a single crash case appears only once in the *crash file.* The *vehicle file* contains data on all responsible and non-responsible vehicles that are involved in a crash, and accordingly a single crash case may appear more than once in the *vehicle file* depending on the number of vehicles involved in the crash. A crash record in the *vehicle file* can be sorted using both the “Accident Number” variable and “Vehicle Number” variable that is used as an identification number for each vehicle in the crash. The *person file* contains data on all responsible and non-responsible persons that are involved in the crash. Crash persons include pedestrians, pedal cyclists and other non–motorists involved in the crash. A single crash case may occupy multiple rows in the *person file* depending on the number of persons involved in a crash. To analyze all the injuries and damage caused by each recorded crash, the *vehicle file* and the *person file* are merged in this study using the “Accident Number” in the *accident file* and the “Vehicle Number” in the *vehicle file*.

Work zone crashes were grouped in three data sets to enable a comprehensive analysis of three different types of work zone crashes: (1) fatal crashes; (2) multi-vehicle injury crashes; and (3) single-vehicle injury crashes. The analysis of the third type of crashes involving only one vehicle was performed to provide an additional investigation of these crashes that have a higher probability of being caused by the work zone layout compared to multiple vehicle crashes that can be caused by other vehicles and not necessarily the work zone. Accordingly, the following three datasets were extracted from the NHTSA data files for detailed analysis: (1) *fatal work zone crashes* for a 10 year period from 1996 to 2005 that include 270 crashes; (2) *all injury work zone crashes involving one or more vehicle* for a 5 year period from 2001 to 2005 that include 9,090 crashes; and (3) *injury work zone crashes involving only one vehicle* for a 5 year period from 2001 to 2005 that include 2,126 crashes. It should be noted that the analyzed period for injury crashes was 5 years because it contained adequate number of crash records while the equivalent period for fatal crashes was 10 years because the available crash records in the 5 year period was not adequate for the analysis.

Many procedures were developed in SAS 9.2 to automate the process of crash data fusion that was performed in five main steps. The first step focused on developing SAS procedures to automate extracting work zone related crash records from all the available NHTSA crash records and combining them in a single spread sheet. These work zone crashes were identified as a subset of the entire crash data set using the variable “RD_CON1” in the *crash file* that represents roadway condition and has 12 possible values, as shown in Table 3.2. The values of 2, 3, 4, and 5 for this variable represent construction zone, maintenance zone, utility work zone, and work zone unknown, respectively. All crashes that had these values were extracted and listed under a new variable named “Road Condition”. The second step developed SAS procedures to automate extracting work zone injury and fatal crash records after excluding property damage only (PDO) work zone crashes. Identifying injury and fatal crashes was performed using the variable “SEVERITY” in the *crash file* that represents the most severe injury sustained by any occupant or non-occupant involved in the crash. The data files from 1996 to 2003 used the numerical values of 1 and 2 to represent fatal and injury crashes, while the data files of 2004 and 2005 used the alphabetical values of F and I to represent fatal and injury crashes, respectively as shown in Table 3.3. The third step developed SAS procedures to automate the integration and joining of the *crash, vehicle, and person files* using both the “Accident Number” variable in the *accident file* and the “Vehicle Number” variable in the *vehicle file* as described earlier. Whenever ambiguous or incomplete data were encountered in the data sets, IDOT officials were consulted to provide clarification and guidance. The fourth step focused on developing SAS procedures to automate the extraction of the aforementioned three data subsets that contain: (1) *fatal work zone crashes* for a 10 year period from 1996 to 2005 that include 270 crashes; (2) *Injury work zone crashes involving one or more vehicle* for a 5 year period from 2001 to 2005 that include 9,090 crashes; and (3) *Injury work zone crashes involving only one vehicle* for a 5 year period from 2001 to 2005 that include 2,126 crashes. The fifth step involved regrouping work zone crash variables into 5 main categories as shown in Table 3.4.

In order to statistically identify the characteristics of work zones associated with the time of the accident, the observations of time were regrouped and organized into four periods: (1) 6:01AM – 10:00 representing the peak morning hours; (2) 10:01 – 16:00 representing the daytime non-peak hours; (3) 16:01 – 20:00 representing the afternoon/evening peak hours; and (4) 20:01 – 6:00AM representing the nighttime hours. In a similar way, the observations associated with the driver contributing causes include 31 categories representing all possible contributing causes of a crash such as: failed to yield, disregarded control devices, too fast for conditions, wrong way/side, and followed too closely. These 35 different contributing causes were regrouped and organized into 6 major categories: (1) improper driving; (2) distraction; (3) work zone environment; (4) disregarding traffic control; (5) speed; and (6) unknown. The complete list of contributing causes is listed in Appendix A, Table A-11-A while the comprised list is presented in Appendix A, Table A-11-B.

Table 3.2 NHTSA Road Condition Variable

Variable	Possible Values	Description
Road Condition: indicates a deficiency in the road where the crash occurred.	0	Not stated
	1	No defects
	2	Construction zone
	3	Maintenance zone
	4	Utility work zone
	5	Work zone—unknown
	6	Shoulders
	7	Ruts/holes
	8	Worn surface
	9	Debris on roadway
	10	Other
	99	Unknown

Table 3.3 NHTSA Accident Severity Variable

Variable	Possible Values	Description
Accident Severity: indicates the most severe injury sustained by any occupant or non-occupant involved in the crash.	1,F	Fatal
	2,I	Injury
	3,P	Property Damage Only (PDO)

Table 3.4 Crash Data Categories and Associated Variables

Category	Variable	Observations
1. Time Data	1- Time of the accident	See Appendix A: Table 1
	2- Day of the week	See Appendix A: Table 2
2. Crash Data	3- Total number of fatalities and injuries	Using actual numbers
	4- Number of vehicles involved	Using actual numbers
	5- Type of collision	See Appendix A: Table 3
3. Road Data	6- Class of traffic way	See Appendix A: Table 4
	7- Federal classification of highway	See Appendix A: Table 5
	8- Work zone type	See Appendix A: Table 6
	9- Road surface	See Appendix A: Table 7
	10- Route prefix	See Appendix A: Table 8
	11- Traffic control	See Appendix A: Table 9
	12- Traffic control functionality	See Appendix A: Table 10
4. Contributing Cause Data	13- Contributing Cause1&2	See Appendix A: Table 11
5. Light and Weather Data	14- Light Condition	See Appendix A: Table 13
	15- Weather	See Appendix A: Table 14

A sample of the spreadsheet that includes the first dataset of fatal work zone crashes is presented in Table 3.5. The spreadsheet was designed to include all the available data in the data files obtained from the National Highway Traffic Safety Administration (NHTSA).

Table 3.5 Sample NHTSA Dataset of Fatal Illinois Work Zone Crashes in 2005

Crash	Time Information			Accident Severity			Crash Information					
Number	Date of Accident	Time of Accident	Day of Week	Number of Fatalities	Number of Injuries	Total number Inj & Fat	County	Population Group	Enforcement Agency	Intersection Related	Number of Vehicles	Type of Collision
50000645	1172005	4	1	1	0	1	16	3	3	2	1	8
50056209	2272005	4	7	1	0	1	16	3	3	2	1	6
50075837	2272005	4	7	1	5	6	16	3	3	2	2	7
50150994	3022005	4	3	1	1	2	69	0	3	2	2	14
50199199	2282005	1	1	1	1	2	49	6	1	1	2	10
50301647	3072005	3	1	1	4	5	84	9	1	1	4	15
50349786	5072005	3	6	1	0	1	82	0	3	2	1	7
50442409	5182005	2	3	1	1	2	16	5	3	2	6	11
50514694	5182005	2	3	1	0	1	99	0	3	2	2	11
50780139	6242005	2	5	3	0	3	101	7	3	2	4	11
50808955	6122005	2	7	1	3	4	11	0	3	2	3	14
51648947	8052005	4	5	1	0	1	16	3	3	2	1	1
51653186	8292005	1	1	1	0	1	16	7	3	2	2	7
51685154	8312005	1	3	1	0	1	75	0	3	2	1	6
51731727	8312005	4	3	1	2	3	16	7	3	2	3	11
52009198	9052005	1	1	1	0	1	84	9	1	2	1	5
52154507	9272005	2	2	1	1	2	22	8	1	2	3	15
52155181	9262005	4	1	2	0	2	16	3	3	2	2	11
52376985	10142005	1	5	1	0	1	16	8	1	2	1	2
52807021	11162005	4	3	1	1	2	16	3	3	2	2	11
52807385	11192005	4	6	1	0	1	50	6	3	2	2	6

Table 3.5 (Continued) Sample NHTSA Dataset of Fatal Illinois Work Zone Crashes in 2005

Crash Number	Roadway Information							Contributing Causes		Climatic Information	
	Class of Trafficway	Federal Classification of Highways	Road Condition	Road Surface	Route Prefix	Traffic Control	Traffic Cont Functionality	Contributing Cause1	Contributing Cause2	Light Condition	Weather Condition
50000645	5	1	2	1	9	12	4	15	0	5	1
50056209	5	1	2	1	9	11	4	1	20	5	1
50075837	5	1	2	1	9	12	4	8	27	5	1
50150994	2	3	2	1	1	12	4	19	20	4	1
50199199	6	3	2	2	5	3	4	25	99	1	3
50301647	6	3	2	1	5	3	4	2	99	5	1
50349786	5	1	2	1	9	99	2	19	20	1	1
50442409	8	1	2	1	9	12	4	28	27	1	1
50514694	1	1	2	1	9	12	4	28	27	1	1
50780139	5	1	2	1	9	1	1	28	18	1	1
50808955	2	4	2	2	5	1	1	20	15	1	2
51648947	5	1	2	1	9	12	4	24	99	5	1
51653186	8	1	2	1		4	1	15	15	1	1
51685154	2	5	3	1	5	10	4	18	0	1	1
51731727	8	1	2	1	9	11	4	28	3	5	1
52009198	7	14	2	1	8	1	1	0	0	1	1
52154507	6	3	2	1	5	11	4	18	99	1	1
52155181	5	1	2	1	9	12	4	1	2	5	1
52376985	8	17	2	1		1	1	0	0	1	1
52807021	5	1	2	1	9	11	4	1	99	5	1
52807385	8	17	2	1		11	4	24	50	4	1

3.3.2 Highway Safety Information System Crash Data Fusion

The most recent five years (2003-2007) of crash records that were released from the Highway Safety Information System database for the state of Illinois included a total of 875,537 records from January 1, 2003 to December 31, 2007, including 1,729 work zone crash records that represent all recorded injury and fatal work zone crashes. These crash records were stored in three separate SAS subfiles: (1) crash data subfile which can be sorted and organized using the crash case number; (2) vehicles and occupants data subfile which can be linked to the first crash subfile using the crash case number and vehicle number; and (3) roadlog subfile which can be linked to the first crash subfile using three variables: county, route, and milepost.

The HSIS work zone crash dataset was extracted and fused using SAS 9.2 in five main steps. Similarly to NHTSA dataset, many SAS procedures were developed to extract and fuse work zone injury crashes. The first step involved extracting work zone crash records from all the available records and combining them in a single spread sheet. These work zone crashes were identified as a subset of the entire crash data set based on the variable "RD_DEF" in the data file that uses the values of 02, 03, 04, and 05 to represent construction zone, maintenance zone, utility work zone, and work zone unknown, respectively as shown in Table 3.6. This variable was renamed in the current analysis as "Type of Construction". The second step involved extracting work zone injury and fatal crash records excluding property damage only (PDO) work zone crashes. Identifying injury and fatal crashes was performed using the variable "SEV_CDE" that represent the crash severity and has four possible categories including categories 01 and 02 that represent fatal and injury crashes, respectively, as shown in Table 3.7. The third step involved joining crash files and roadlog files using both

“Cntyrte: County Route” and “milepost” in crash files and matched with “cnty_rte: County Route” and “begmp: Beginning milepost” in roadlog files. This link resulted in a dataset that included records of 1,729 work zone injury and fatal crashes with data on 31 different variables, as shown in Table 3.8. Whenever ambiguous or incomplete data were encountered in the data set, IDOT officials and HSIS personnel were consulted to provide clarification and guidance. The fourth step of preparing the dataset for the correlation analysis was to regroup the 31 crash variables under six major categories as shown in Table 4.8. The fifth step involved regrouping the observations of 4 variables into certain categories. The variables and their new categories are shown in Table 3.9.

Table 3.6 Road Defects

Variable	Number	Description
RD_DEF: indicates the road Defects	0, 99	Not stated or Unknown
	01	No Defects
	02	Construction Zone
	03	Maintenance Zone
	04	Utility Work Zone
	05	Work Zone Unknown
	06	Shoulder HGH, LO, SFT
	07	Ruts, Holes, Bumps
	08	Worn Surface
	09	Debris on Roadway
	10	Other
	11	Loose Materials
	12	Low Shoulder

Table 3.7 Road Crash Severity

Variable	Number	Description
SEV_CDE: indicates the crash severity	0	Not Coded
	01	Fatal
	02	Injury
	03	Property Damage Only

Table 3.8 Dataset of Work Zone Injury and Fatal Crashes

SAS Variable Name	Description	Observations
1. CASENO	CaseNumber	Using actual numbers
2. ACCYR	AccYear	Using actual numbers
3. HOUR	AccHour	See Appendix A: Table 1
4. SEV_CDE	Severity	See Appendix A: Table 15
5. SEVERITY	InjurySeverity	See Appendix A: Table 16
6. TOT_KILLED	TotalKilled	Using actual numbers
7. TOT_INJ	TotalInjured	Using actual numbers
8. ACCTYPE_POST_93	TypeCollision	See Appendix A: Table 3
9. NUMVEHS	NumberVehicles	Using actual numbers
10. CAUSE1	Cause1	See Appendix A: Table 11
11. CAUSE2	Cause2	See Appendix A: Table 11
12. TRFCNTL	TrafficContType	See Appendix A: Table 9
13. TC_COND	TrafficContCondition	See Appendix A: Table 10
14. RODWYCLS	RoadClassification	See Appendix A: Table 17
15. CLS_TFWY	ClassTrafficway	See Appendix A: Table 4
16. RTE_PREF	RoutePrefix	See Appendix A: Table 8

Table 3.8 (Continued) Dataset of Work Zone Injury and Fatal Crashes

SAS Variable Name	Description	Variable File
17. ONEWAY	OnewayIndicator	See Appendix A: Table 18
18. INT_REL	IntersectionRel	See Appendix A: Table 19
19. RD_DEF	TypeConstruction	See Appendix A: Table 6
20. NO_LANES	NumberLanes	Using actual numbers
21. SURF_TYP	SurfaceType	See Appendix A: Table 20
22. RDSURF	RoadSurfaceCond	See Appendix A: Table 7
23. MED_TYPE	MedianType	See Appendix A: Table 21
24. MEDWID	MedianWidth	See Appendix A: Table 22
25. AADT	AADT	See Appendix A: Table 23
26. MULTICNT	MultipleDailyVolume	See Appendix A: Table 24
27. COMM_VOL HEAVY	CommercialVolume	See Appendix A: Table 25
28. MVMT	MilVehMiTrv	See Appendix A: Table 26
29. SPD_LIMT	SpeedLimit	Using actual numbers
30. LIGHT	Light	See Appendix A: Table 13
31. WEATHER	Weather	See Appendix A: Table 14

Table 3.9 Regrouped Observations of Four Variables

Variable	**Regrouped Observations**
1- Accident Hour	(1) 6:01AM – 10:00
	(2) 10:01 – 16:00
	(3) 16:01 – 20:00
	(4) 20:01 – 6:00AM
2- Contributing Cause	(1) Improper Driving
	(2) Distraction
	(3) Speed
	(4) Work Zone Environment
	(5) Traffic Control
	(6) Unknown
3- Annual Average Daily Traffic (AADT)	(1) AADT below 10,000
	(2) 10,001 < AADT < 20,000
	(3) 20,001 < AADT < 30,000
	(4) 30,001 < AADT < 40,000
	(5) 40,001 < AADT < 50,000
	(6) AADT over than 50,001
4- CommercialVolume (CV)	(1) CV below 2,000
	(2) 2,001 < CV < 4,000
	(2) 4,001 < CV < 6,000
	(4) 6,001 < CV < 8,000
	(5) 8,001 < CV < 10,000
	(6) CV over than 10,001

All the data for the aforementioned variables had integer values, as shown in the sample spreadsheet that includes the analyzed HSIS dataset and shown in Table 3.10. The spreadsheet containing this data for the identified 1,729 work zone crash records including the values of the aforementioned 31 variables was imported into the SAS software package in order to identify all possible correlations among the 31 variables. The next chapter presents the frequency and severity analysis of work zone crashes gathered by the two aforementioned datasets as well as the contributing causes of correlated variables.

Based on the findings of this analysis, future collection and storage of work zone crash data can be improved by: (1) minimizing variations in data reporting over the years that may undermine the comprehensive analysis of work zone crashes; and (2) updating police crash reports to include more descriptive parameters of the work zone that experienced the crash such as work zone layout and operations type.

Table 3.10 Sample HSIS Dataset of Injury and Fatal Illinois Work Zone Crashes in 2007

Crash Number	Time Information		Crash Information						Contributing Causes			
	AccYear	AccHour	Severity	InjurySeverity	TotalKilled	TotalInjured	TypeCollision	NumberVehicles	Cause1	Cause2	TrafficContType	TrafficContCondition
20070238803	2007	4	2	3	0	1	10	2	1	6	2	2
20072528490	2007	2	2	3	0	1	15	2	4	1	3	4
20072500002	2007	3	2	1	0	2	10	2	1	1	5	4
20070983945	2007	4	1	4	1	0	7	1	5	5	3	4
20071855084	2007	4	2	2	0	2	10	2	1	5	3	4
20075138313	2007	3	2	3	0	1	10	2	1	3	3	4
20074977539	2007	4	2	2	0	2	10	2	1	5	3	4
20073218505	2007	4	2	1	0	2	10	2	1	1	3	4
20072067127	2007	4	2	1	0	3	15	2	1	4	3	4
20071376826	2007	4	2	3	0	1	10	2	1	5	3	4
20074570516	2007	2	2	2	0	3	10	3	4	1	3	4
20072756059	2007	3	2	2	0	1	5	1	3	5	3	4
20073295669	2007	2	2	3	0	1	10	2	1	5	3	3
20073702946	2007	1	2	2	0	1	11	2	1	5	3	4
20072630452	2007	2	2	2	0	1	12	2	1	5	3	4
20071454755	2007	2	2	3	0	1	10	2	6	5	3	4
20071049746	2007	2	2	1	0	1	10	2	4	1	3	4
20072916737	2007	1	2	3	0	2	11	3	6	5	3	4
20073530040	2007	1	2	2	0	1	11	3	1	5	2	2
20073755076	2007	2	2	2	0	3	11	2	1	5	2	2
20071252993	2007	2	2	2	0	1	2	1	5	5	3	4
20070102314	2007	1	2	3	0	1	1	1	4	6	3	4
20075375873	2007	3	2	3	0	2	11	4	6	1	3	4

Table 3.10 (continued) Sample HSIS Dataset of Injury and Fatal Illinois Work Zone Crashes in 2007

Crash Number	Roadway Information											
	RoadClassification	ClassTrafficway	RoutePrefix	OnewayIndicator	IntersectionRel	TypeConstruction	NumberLanes	LaneWidth	SurfaceType	RoadSurfaceCond	MedianType	MedianWidth
20070238803	8	2	5	2	1	2	2	12	560	1	5	3
20072528490	3	6	5	2	1	2	2	12	610	1	0	1
20072500002	4	7	8	2	1	2	4	12	720	1	2	2
20070983945	5	6	1	2	1	2	4	12	610	1	0	1
20071855084	4	6	1	2	1	2	4	12	700	1	7	4
20075138313	4	6	1	2	1	2	4	12	700	1	7	4
20074977539	4	6	1	2	1	2	4	12	700	1	7	4
20073218505	4	6	1	2	1	2	4	12	700	1	7	4
20072067127	4	6	1	2	1	2	4	12	700	1	7	4
20071376826	4	6	1	2	1	2	4	12	700	2	7	4
20074570516	4	6	1	2	1	2	4	12	700	1	7	4
20072756059	4	6	1	2	1	2	4	12	700	1	7	4
20073295669	4	6	1	2	1	2	4	12	600	2	7	4
20073702946	4	6	1	2	1	2	4	12	600	1	5	4
20072630452	5	6	1	2	2	2	6	12	600	1	0	1
20071454755	5	6	1	2	1	2	4	12	600	1	0	1
20071049746	5	6	1	2	1	2	4	10	600	1	0	1
20072916737	4	6	1	2	2	2	4	12	620	1	2	4
20073530040	4	6	1	2	1	2	4	12	600	1	5	4
20073755076	5	6	1	2	1	2	4	12	600	1	0	1
20071252993	3	6	1	2	1	5	2	12	600	1	0	1
20070102314	4	6	1	2	1	3	4	12	600	1	5	4
20075375873	4	6	1	2	1	2	4	12	700	1	7	4

Table 3.10 (continued) Sample HSIS Dataset of Injury and Fatal Illinois Work Zone Crashes in 2007

Crash Number	Traffic Information					Climatic Information	
	AADT	MultipleDailyVolume	CommercialVolume	MilVehMiTrv	SpeedLimit	Light	Weather
20070238803	1	1	1	1	55	4	1
20072528490	2	1	1	1	55	1	1
20072500002	1	1	1	1	40	1	1
20070983945	3	1	1	1	45	5	1
20071855084	3	1	1	1	40	5	1
20075138313	3	1	1	1	40	5	1
20074977539	3	1	1	1	40	5	1
20073218505	3	1	1	1	40	5	1
20072067127	3	1	1	1	40	5	1
20071376826	3	1	1	1	40	5	2
20074570516	3	1	1	1	45	1	1
20072756059	3	1	1	1	45	1	1
20073295669	3	1	1	3	50	1	4
20073702946	4	2	2	1	40	1	1
20072630452	4	1	1	1	30	1	1
20071454755	2	1	2	1	40	1	1
20071049746	3	1	1	2	35	1	1
20072916737	3	1	1	4	55	1	1
20073530040	4	1	2	1	35	1	1
20073755076	4	1	2	1	35	1	1
20071252993	2	1	2	1	25	1	1
20070102314	3	1	1	1	35	9	1
20075375873	5	1	2	6	55	5	1

CHAPTER 4

ANALYSES OF ILLINOIS WORK ZONE CRASHES

4.1 INTRODUCTION

The objective of this chapter is to present a comprehensive analysis of work zone crashes conducted to identify the probable causes and contributing factors of work zone crashes in Illinois. This Chapter focuses on analyzing and identifying contributing factors that cause injury and fatal work zone crashes. The three main objectives of this analysis are to: (1) conduct a statistical analysis to study the frequency and severity as well as other characteristics of (a) fatal work zone crashes; (b) multi-vehicle injury crashes; and (c) single-vehicle injury crashes.; (2) study correlations among all work zone crash variables that were available in the gathered data to investigate the probable causes and contributing factors of work zone crashes in Illinois; and (3) develop guidelines to improve work zone practices in terms of: (a) layout; (b) strategy; (c) standards; and (d) temporary traffic controls. This chapter also presents the development of six crash severity indices to represent the probability of a work zone to experience severe crashes. Work zone crash severity indices represent the probability of a work zone to encounter: (1) severe injury crashes; (2) multi-vehicles crashes; and (3) multi-injuries crashes.

4.2 WORK ZONE CRASH CHARACTERISTICS

All relevant variables to work zone characteristics of the two crash data sets NHTSA and HSIS were grouped in a single spreadsheet and a detailed analysis of crash frequency distribution was conducted to 20 work zone variables grouped in 6 categories presented in Table 4.1. For each of these 20 variables listed in Table 4.1, a comprehensive statistical analysis was conducted to investigate and compare their individual impact on the frequency of: (1) fatal work zone crashes (Fatal); (2) multi vehicle injury work zone crashes involving one or more vehicles (Injury); and (3) single-vehicle injury work zone crashes involving only one vehicle (Injury One-vehicle). The following sections present the main findings of this analysis for each of the twenty variables listed in Table 4.1.

Table 4.1 Work Zone Variables

Category	Variable
1- Road Data	1- Federal Classification of Highway
	2- Work Zone Type
	3- Intersection Relevance
	4- Number of lanes
	5- Lane Width
	6- Median Type
	7- Median Width
	8- Speed Limit
	9- Traffic Control
	10- Traffic Control Functionality
2- Traffic Data	11- Annual Average Daily Traffic (AADT)
	12- Commercial Volume
3- Contributing Cause Data	13- Contributing Cause
4- Crash Data	14- Total Number of Fatalities and Injuries
	15- Number of Vehicles Involved
	16- Type of Collision
5- Environment Data	17- Light Condition
	18- Weather Condition
6- Time Data	19- Day Hour
	20- Weekday

4.2.1 Road Data

This section presents the frequency analysis of road data variables: (1) federal classification of highway; (2) work zone type; (3) intersection relevance; (4) number of lanes; (5) lane width; (6) median type; (7) median width; (8) speed limit; (9) traffic control; and (10) traffic control functionality.

1- Road Data (Federal Classification of Highway)

The impact of the class of the federal classification of highway on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.1(a). The results indicate that "interstate on national highway systems" had the highest percentage of all types of crashes. The results also show that the percentage of fatal work zone crashes on interstates that are not on the national highway system was 11.5% which is much higher than the percentage of injury crashes on the same type of road which was 1%. This suggests that work zones on this class of interstate highways are more likely to cause fatal crashes than injury crashes.

2- Road Data (Work Zone Type)

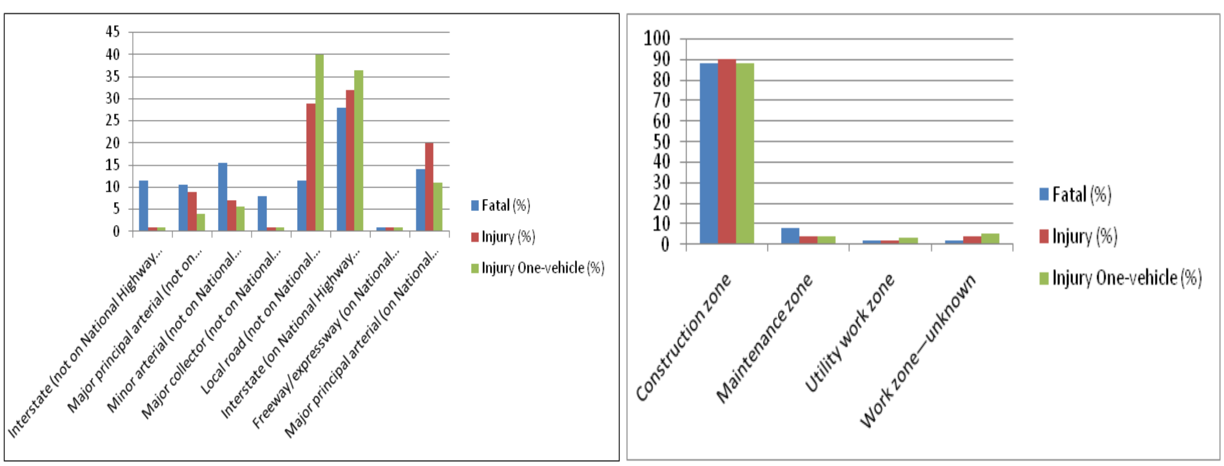
The impact of the work zone type on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.1(b). The work zone variable in this analysis is classified into four types: construction zone, maintenance zone, utility work zone, and unknown work zone. The results clearly show that construction zones were the most dominant type of work zone as they were encountered in 88% of fatal crashes, 90% of injury crashes involving one or more vehicles, and 88% of injury crashes involving only one vehicle. Accordingly, the layout of construction zones needs to be carefully designed and implemented to reduce the risks of fatal and injury crashes and improve traffic safety.

3- Road Data (Intersection Relevance)

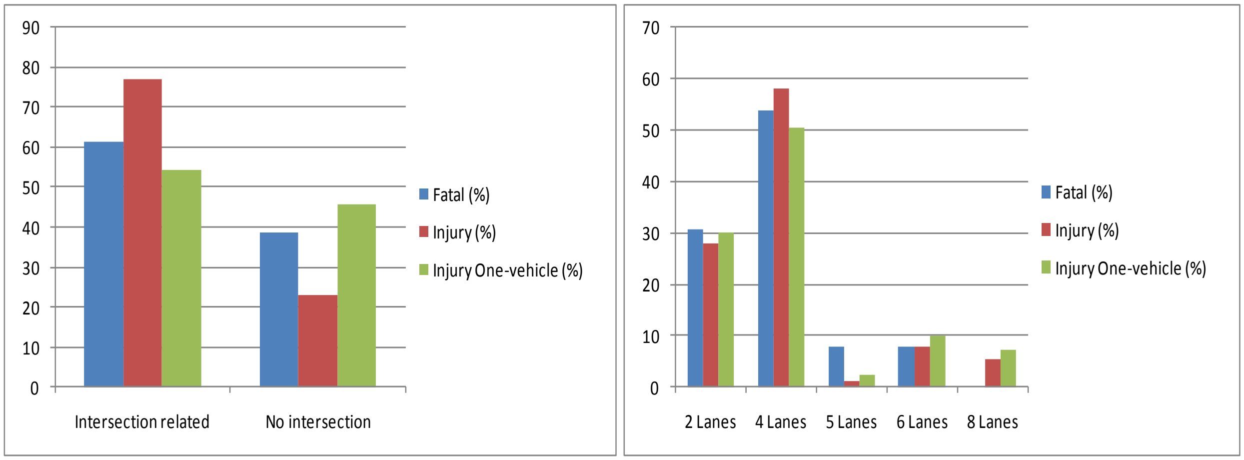
The intersection relevance variable indicates whether the work zone crash occurred at an intersection or not. The impact of intersection on the frequency of fatal and injury work zone crashes in Illinois is shown in Figure 4.1(c). Intersections were obviously among the major contributing factors of work zone crashes since the majority of injury crashes (77%) occurred at intersections. Similarly more than 60% of fatal crashes occurred at intersections. This result indicates the importance of emphasizing additional safety countermeasures at entrance and exit ramps to avoid associated work zone crashes.

4- Road Data (Number of Lanes)

The impact of the number of lanes on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.1(d). The results clearly show that highways of 4 lanes were the most dominant highways where work zone crashes occurred. More than 50% of fatal and injury crashes occurred on 4-lane highways. This result confirms that "interstate on national highway systems" of 4-lanes are having the highest percentage of all types of crashes.



(a) Figure 4.1 (b)



(c) **(d)**

Figure 4.1 Impact of road characteristics on the frequency of fatal and injury crashes: (a) federal classification of highway; (b) work zone type; (c) intersection relevance; and (d) number of lanes

5- Road Data (Lane Width)

The lane width as an impact factor on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.2(a). The results clearly show that work zones of standard lane width of 12-ft had the highest percentage of work zone crashes. More than 84% of fatal crashes and 77% of injury crashes occurred on traffic lanes of 12-ft width. Shrinking traffic lane widths below 12-ft only resulted in 15% of total injury crashes which indicate that lane width is not a dominant factor of work zone crashes.

6- Road Data (Median Type)

The median type variable has 7 observations; (1) no median; (2) unprotected, treated earth; (3) curbed, raised; (4) positive barrier, fencing, guard rail, retaining wall; (5) rumble strips; (6) painted; and (7) mountable median. The impact of median type on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.2(b). The frequency analysis show that almost 40% of work zone fatal and injury crashes occurred in roadways of no median compared while 15% of crashes occurred in road ways that had positive barrier whether it is fencing, guard rail, or retaining wall. Less than 3% of work zone crashes occurred in roadways with rumble strips.

7- Road Data (Median Width)

The impact of median width on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.3(c). The frequency analysis show that almost 40% of work zone fatal and injury crashes occurred in roadways of no median to match the median type aforementioned result. The increase of median width did not show a relevant decrease of neither fatal nor injury work zone crashes which indicate that median width has no significant impact on work zone crashes.

8- Road Data (Speed Limit)

The speed limit variable represents the posted roadway speed limit. The impact of speed on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.4(d). The majority of fatal crashes (~62%) occurred at higher speed limits (+55 mph) compared with less injury crashes (25%) at the same speed limits which clearly indicate the severity of work zone crashes at higher speed limits. The percentage of fatal crashes significantly dropped to less than 8% for construction zones that had a speed limit of 40 mph or lower.

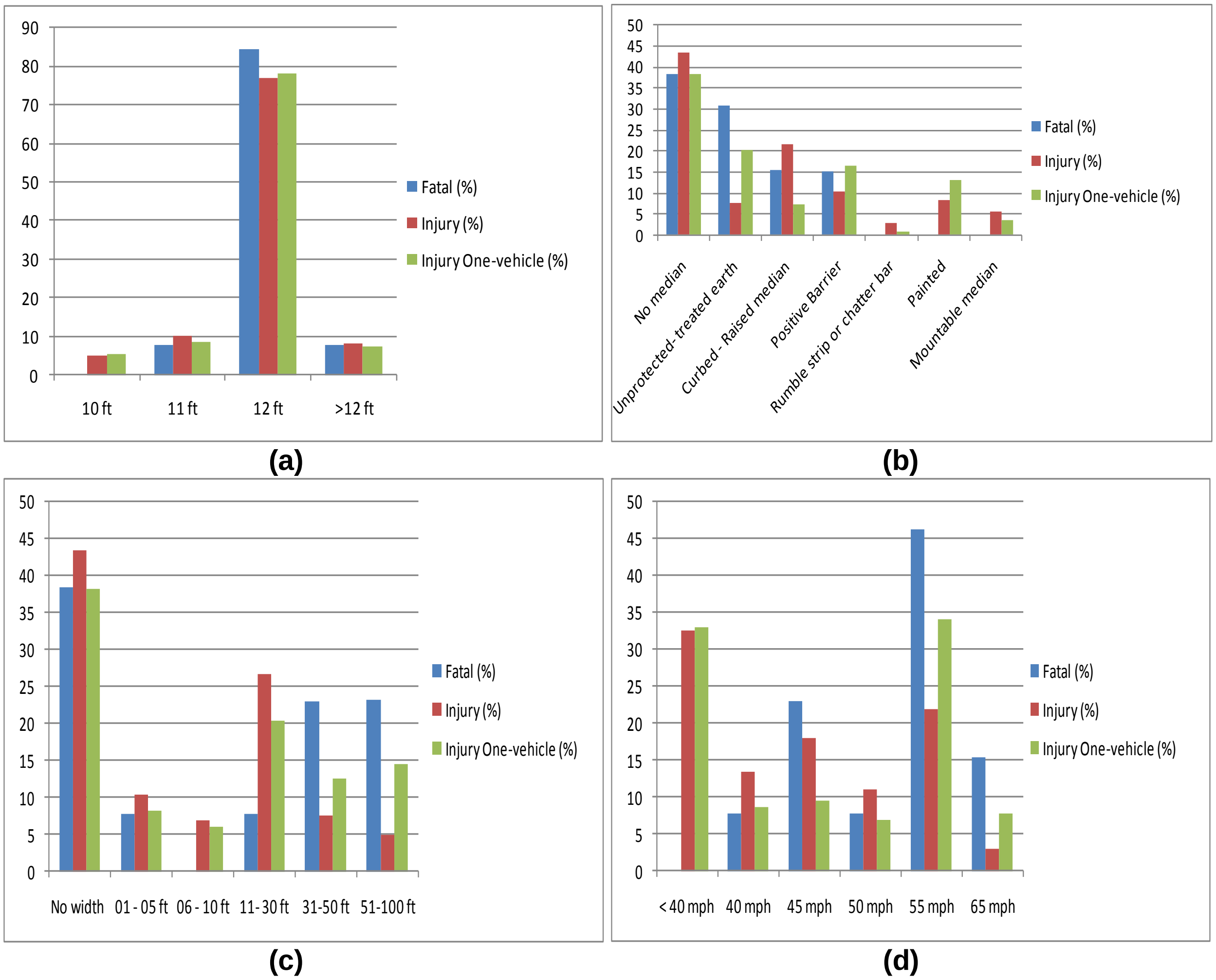


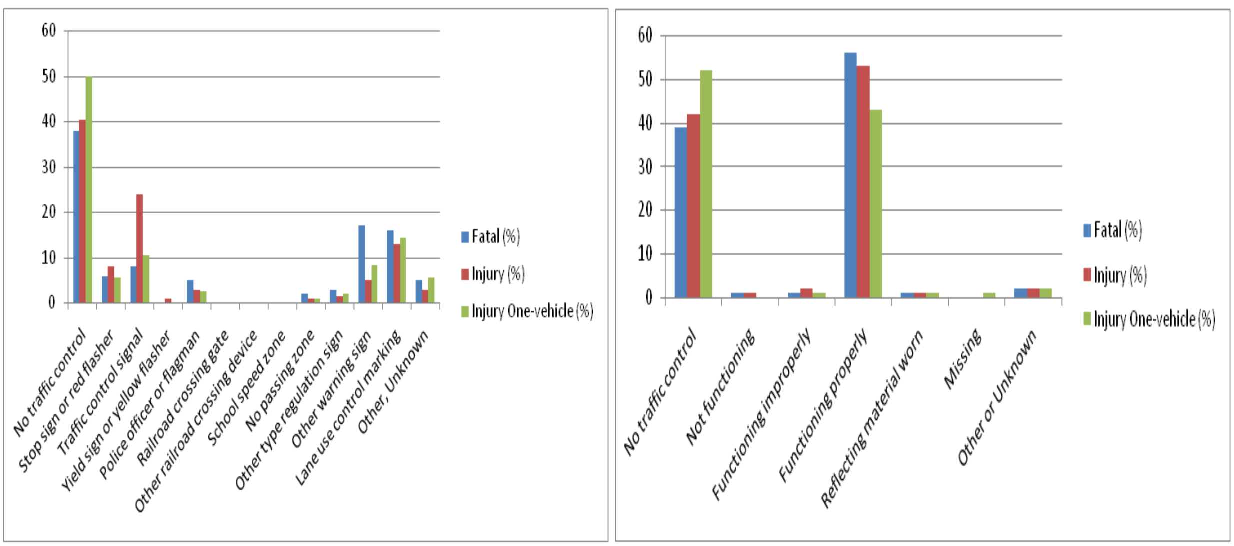
Figure 4.2 Impact of road characteristics on the frequency of fatal and injury crashes: (a) lane width; (b) median type; (c) median width; and (d) speed limit

9- Road Data (Traffic Control)

The impact of utilizing various traffic control devices on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.3(a). The results show that approximately 40% of fatal and injury work zone crashes had no traffic control. This finding was discussed with IDOT personnel and they clarified that police officers sometimes misinterpret the meaning of “No traffic control” and report it as an indication that there is no traffic control signal. The results also show that the presence of a police officer or a flagman in a work zone is an effective traffic control measure as its utilization was reported in only 5% of the fatal crashes and 3% of the injury crashes.

10- Road Data (Traffic Control Functionality)

The impact of traffic control functionality on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.3(b). The results show that 56% of fatal crashes and 53% of injury crashes occur in work zones that have traffic control devices that are functioning properly. The remaining fatal and injury work zone crashes (i.e., 44% and 47%) occur in work zones that have no or malfunctioning traffic control devices.



(a) **(b)**

Figure 4.3 Impact of road characteristics on the frequency of fatal and injury crashes: (a) traffic control type; and (b) traffic control functionality

4.2.2 Traffic Data

This section presents the frequency analysis of traffic data variables: (1) AADT; and (2) Commercial Volume.

11- Traffic Data (Annual Average Daily Traffic - AADT)

The AADT minimum value was 700 while the maximum was 293,600. Therefore, all roads' AADT values where crashes occurred were regrouped in six subcategories as shown in Table 4.2. The impact of AADT on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.4(a). The results show that more than 30% of fatal work zone crashes occurred at low AADT (below 10,000) which indicate that the AADT does not affect the severity of work zone crashes. Almost 30% of injury work zone crashes occurred at AADT between 10,000 and 20,000. Beyond that peak range, the rate of work zone crashes tends to gradually decrease in roads with higher ranges of AADT.

Table 4.2 Observations for AADT

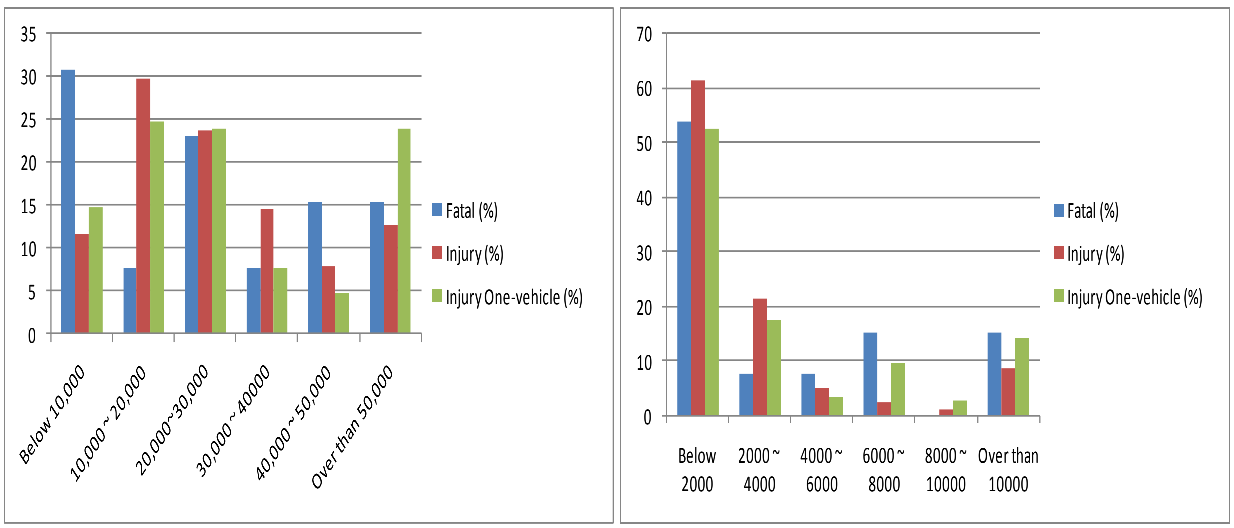
Variable	Number	Description
AADT: indicates the annual average daily traffic of the roadway	1	Below 10,000
	2	10,000 ~ 20,000
	3	20,000~30,000
	4	30,000 ~ 40000
	5	40,000 ~ 50,000
	6	Over than 50,000

12- Traffic Data (Commercial Volume)

The Commercial Volume variable represents the percentages of truck-related "Heavy Commercial Volumes” which include two-axle trucks with six or more tires, multi-axle vehicles", single trucks, tractor-semi combinations, and buses (HSIS 2009). Commercial volume records were regrouped in six subcategories as shown in Table 4.3. The impact of commercial volume on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.4(b). The results show that the majority of work zone crashes whether fatal or injury occurred in roads with commercial volume below 2000. The rate of work zone crashes tends to gradually decrease as the commercial volume of the road increases.

Table 4.3 Observations for Commercial Volume

Variable	Number	Description
Commercial Volume: indicates the annual average daily traffic of the roadway	1	Below 2000
	2	2000 ~ 4000
	3	4000 ~ 6000
	4	6000 ~ 8000
	5	8000 ~ 10000
	6	Over than 10000



(a) **(b)**

Figure 4.4 Impact of traffic data on the frequency of fatal and injury crashes: (a) AADT; and (b) commercial volume

4.2.3 Contributing Cause Data

The contributing cause variable represents various drivers' actions that contributed to the crash. In the NHTSA data files, this variable has 31 possible values to represent all possible contributing causes that are related to drivers' actions. In this analysis, these 31 possible values are regrouped and divided into 6 major contributing causes that are related to the drivers' actions: (1) improper driving; (2) distraction; (3) work zone environment; (4) disregarding traffic control; (5) speed; and (6) unknown.

13- Contributing Cause

The impact of these contributing causes on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.5. The results show that improper driving was the highest contributing cause (36%) for both fatal and injury work zone crashes, followed by speed and work zone environment causes. The improper driving category covers a number of driver actions such as following too closely, wrong side/way, improper turn, and right turn on red. The work zone environment was responsible for more than 30% of single vehicle injury crashes and almost 20% of fatal and multi-vehicle crashes. Work zone environment category covers a number of subcategories such as: road engineering /surface /markings/defects; road construction; vision obscured; and improper lane usage. Accordingly, the layout of construction zones needs to be carefully designed and implemented to minimize these potential crash causes in order to reduce the risks of fatal and injury crashes and improve traffic safety.

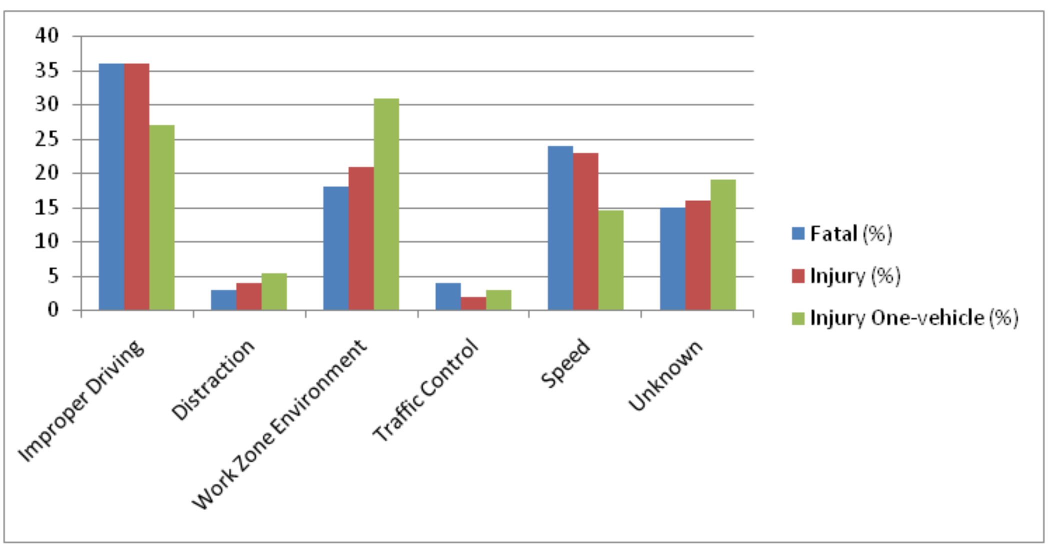


Figure 4.5 Impact of various contributing causes on the frequency of fatal and injury crashes

4.2.4 Crash Data

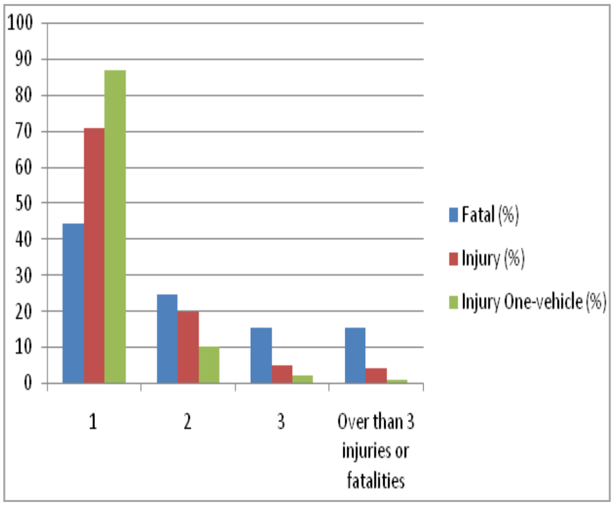
This section presents the frequency analysis of crash data variables: (1) total number of fatalities and injuries; (2) number of vehicles involved; and (3) type of collision.

14- Crash Data (Total Number of Fatalities and Injuries)

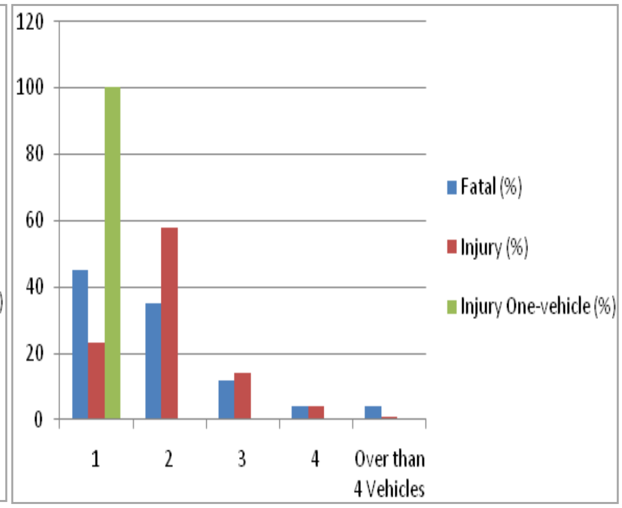
Work zone crashes are classified as fatal crashes if they result in at least one fatality and injury crashes if they cause only injuries. In this analysis, the severity of different types of crashes is investigated using a new metric/variable that represents the total number of fatalities and injuries that are caused by the crash. The results of this analysis show that the majority of injury crashes (71% and 87% of the two analyzed injury crashes) caused only one injury, as shown Figure 4.6(a). On the other hand, fatal crashes were more severe as the majority of those (55.5%) caused two or more injuries and/or fatalities.

15- Crash Data (Number of Vehicles Involved)

In this analysis, the severity of various types of crashes is analyzed using a second metric that represents the total number of vehicles involved in the crash. The results of this severity analysis are shown in Figure 4.6(b). The results show that almost half of fatal work zone crashes (45%) involved one vehicle only while a small percentage (20%) of these crashes involved three or more vehicles. On the other hand, 23% of injury work zone crashes involved one vehicle only while 58% of this type of crashes were caused by two vehicles. This indicates that (a) fatal crashes are more likely to involve one vehicle compared to injury crashes; and (b) a significant majority of all types of crashes involve one and two vehicles.



(a)



(b)

Figure 4.6 Impact of crash data on the frequency of fatal and injury crashes: (a) total number of fatalities and injuries; and (b) number of vehicles involved

16- Crash Data (Type of Collision)

This section analyzes the types of collisions caused by fatal and injury crashes as shown in Figure 4.7. The results of this analysis show that the most frequent type of collision was rear-end for both fatal crashes (22%) and all injury crashes (43%). For injury crashes involving only one vehicle, fixed object collision was the most frequent type of crash (37%). The results also indicate that rear-end and fixed object are the leading types of collisions for fatal and injury work zone crashes in Illinois.

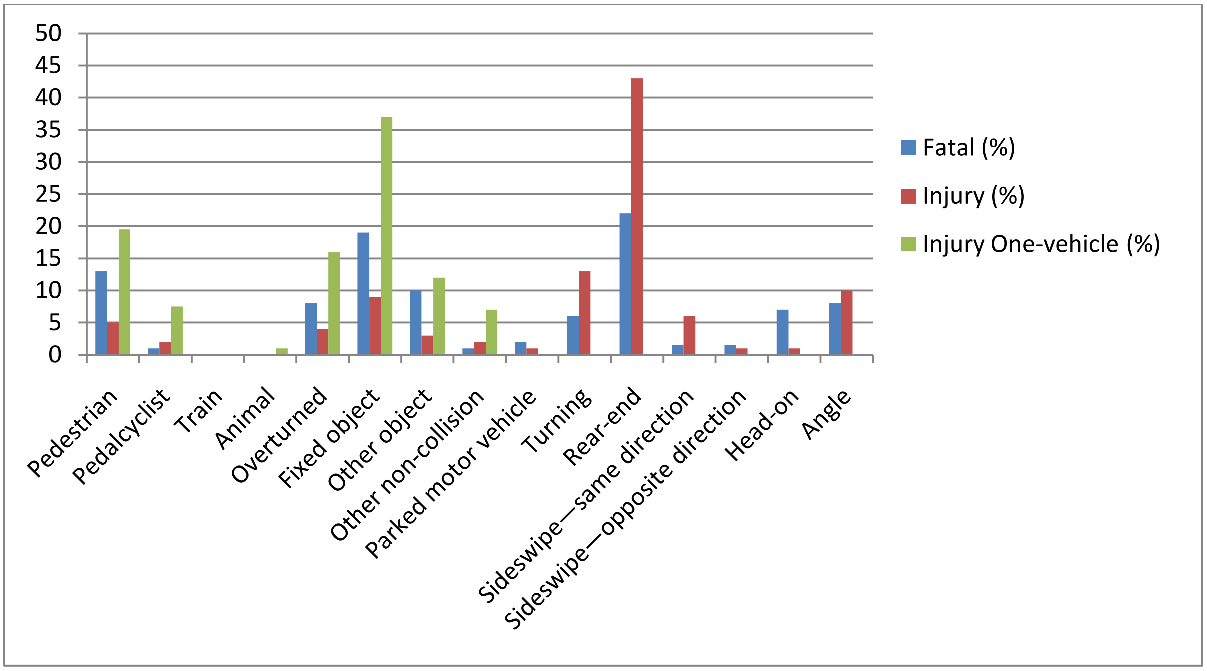


Figure 4.7 Impact of type of collision on the frequency of fatal and injury crashes

4.2.5 Environment Data

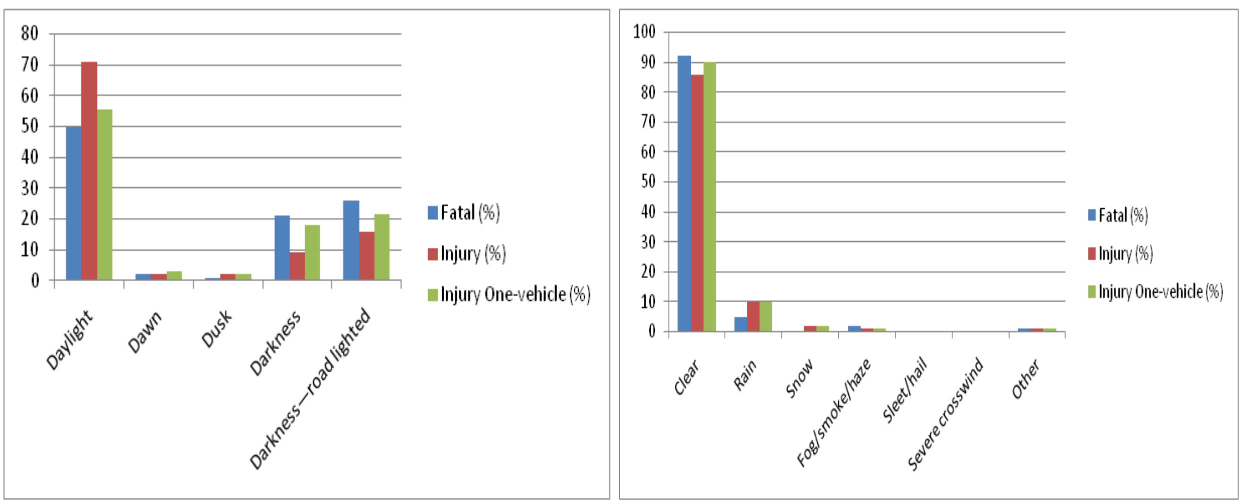
This section presents the frequency analysis of environment data: (1) light condition; and (2) weather condition.

17- Environment Data (Light Condition)

The impact of the light conditions on the frequency of fatal and injury crashes in Illinois is shown in Figure 8(a). The results show that 50% of fatal crashes and 71% of injury crashes occurred at daylight condition. The remaining fatal and injury work zone crashes (i.e., 50% and 29%) occurred during darkness, dawn and dusk. The results also show that 21% of fatal crashes occurred at darkness without road lighting compared to 9% of total injury crashes that occurred in a similar lighting condition. This suggests that nighttime work zones in roads that are not lighted are more likely to cause fatal crashes than injury crashes. Accordingly, the lighting conditions in these nighttime work zones need to be carefully designed and implemented to improve visibility and traffic safety.

18- Environment Data (Weather Condition)

The impact of the weather conditions on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.8(b). The results show that the majority of work zone crashes occurred during clear weather condition. Only 10% of total injury crashes occurred on rainy conditions which suggest that weather is not a major contributing cause of work zone crashes in Illinois. IDOT resident engineers have indicated that the main reason that weather conditions were not among the major contributing causes of work zone crashes was due to work zone procedures that halt operations during inclement weather conditions to ensure the safety of the travelling public as well as construction workers.



(a) **(b)**

Figure 4.8 Impact of environment characteristics on the frequency of fatal and injury crashes; (a) light condition; and (b) weather condition

4.2.6 Time Data

This section presents the crash frequency analysis of time data: (1) day hour; and (2) weekday.

19- Time Data (Day Hour)

The impact of the time of day on the frequency of fatal and injury crashes in Illinois is shown in Figure 4.9(a). The results indicate that 44% and 40.5% of fatal crashes and injury crashes involving only one-vehicle, respectively, occurred at nighttime hours (20:00-6:00 am). These findings suggest that nighttime work zones create safety risks for traffic and cause a significant percentage of the total number of fatal crashes and injury crashes involving one vehicle only. These increased nighttime risks need to be carefully considered and addressed in the layout and lighting design of nighttime work zones to improve their visibility and improve the alertness of nighttime drivers. For injury crashes involving one or more vehicles, the results show that 37.5% of these crashes occurred during the daytime non-peak hours (10:01-16:00). One possible explanation for this finding is that higher traffic volumes during the morning peak hours (6:01 to 10:00 am) and afternoon hours (16:01 to 20:00) often cause a slowdown in traffic which reduces the risks of work zone crashes during these periods compared to that experienced during daytime non-peak hours.

20- Time Data (Weekday)

The impact of the day of the week on the frequency of fatal and injury crashes is shown in Figure 4.9(b). The results show that there is no significant difference between the different types of work zone crashes and their distributions over the seven days of the week. For fatal work zone crashes for example, the largest difference was only 5% and it was encountered between the percentage of crashes occurring on Wednesday and Saturday (17%) and those occurring on Thursday and Sunday (12%). The results also show that the least percentage of fatal and injury work zone crashes occur on Sunday which can be explained by the typical low traffic on that day of the week.

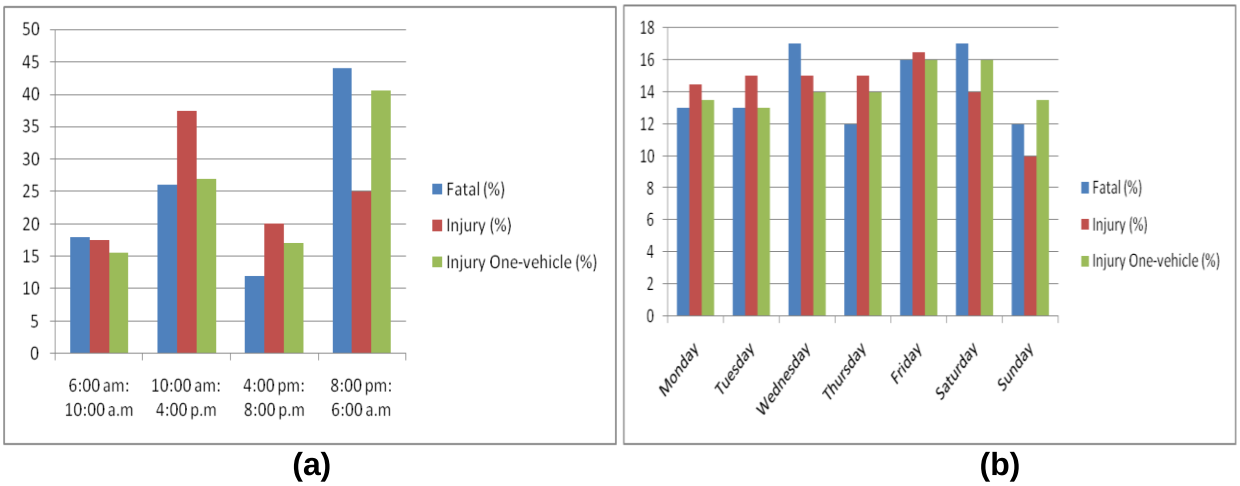


Figure 4.9 Impact of time on the frequency of fatal and injury crashes; (a) day hour; and (b) weekday

4.2.7 Summary of Work Zone Crash Characteristics

The statistical analysis of work zone crashes in the previous sections focused on studying the impact of 20 work zone parameters gathered from two datasets; (1) NHTSA; and (2) HSIS data on the frequency of three types of work zone crashes; (1) fatal crashes; (2) multi-vehicle injury crashes; and (3) single-vehicle injury crashes. The main findings of this analysis include:

1- A significant percentage of fatal crashes (44%) and injury crashes involving one-vehicle (40.5%) occurred at nighttime (20:00-6:00AM). This suggests that nighttime work zones create potential safety risks and may cause a significant percentage of the total number of fatal crashes and injury crashes involving one vehicle. These increased nighttime risks need to be carefully considered and addressed in the layout and lighting design of nighttime work zones to improve their visibility and improve drivers alertness.

2- The day of the week is not a significant factor that affects the frequency of work zone crashes in Illinois. The results also show that the least percentages of fatal and injury work zone crashes occur on Sunday which can be explained by the typical low traffic on that day.

3- The majority of injury crashes (71%) caused only one injury while fatal crashes were more severe as the majority of them (55.5%) caused two or more injuries and/or fatalities.

4- A significant majority of all types of crashes involve one and two vehicles and fatal crashes are more likely to involve one vehicle compared to injury crashes.

5- Rear-end and fixed object collisions are the leading types of fatal and injury crashes in Illinois. The most frequent type of collision was rear-end for both fatal crashes (22%) and injury crashes involving one or more vehicles (43%). For injury crashes involving only one vehicle, fixed object collision was the most frequent type of crash (37%).

6- The class of traffic way affects the rate of work zone crashes as “urban-city streets” had the highest percentage of all types of crashes. For fatal crashes, “rural-other marked state highway” and “urban-other marked state highway” were the second and third types of traffic ways in terms of crash rates. For injury crashes, “urban-other marked state highway” and “urban-controlled access highway” were the second and third types of traffic ways in terms of crash rates.

7- The Federal highway classification has an impact on the rate of work zone crashes as “interstate on national highway systems” had the highest crash rate for fatal and injury crashes. The results also show that the rate of fatal work zone crashes on “interstates that are not on the national highway system” was 11.5% which was much higher than the rate of injury crashes on the same type of road which was 1%.

8- Interstate roads had the highest percentage of fatal crashes (40%) while U.S. routes had the highest percentage of both types of injury crashes (42% and 50.5%).

9- The presence of a police officer or a flagman in a work zone is an effective traffic control measure as its utilization was reported in only 5% of the fatal crashes and 3% of the injury crashes.

10- The majority of fatal crashes (56%) and injury crashes (53%) occurred in work zones that had traffic control devices that were functioning properly. The remaining fatal and injury work zone crashes (i.e., 44% and 47%) occurred in work zones that had no or malfunctioning traffic control devices.

11- Improper driving was the highest contributing cause of both fatal and injury work zone crashes, followed by speed and work zone environment causes. The improper driving category covers a number of driver’s actions such as following too closely, wrong side/way, improper turn, and right turn on red. The speed category covers speed related actions while the work zone environment category covers a number of subcategories such as road engineering/surface/markings /defects, road construction, obscured vision, and improper lane usage. Accordingly, the layout of construction zones needs to be carefully designed and implemented to minimize these potential crash causes in order to reduce the risks of fatal and injury crashes.

12- A significant percentage of fatal and injury work zone crashes (50% and 29%) occurred during darkness, dawn and dusk. The results also show that 21% of fatal crashes occurred at darkness without road lighting compared to 9% of total injury crashes that occurred in a similar lighting condition. This suggests that nighttime work zones in roads that are not lighted are more likely to cause fatal crashes than injury crashes. Accordingly, the lighting conditions in these nighttime work zones need to be carefully designed and implemented to improve visibility and traffic safety.

13- The majority of work zone crashes occurred during clear weather condition and only 10% of total injury crashes occurred at rain condition which suggests that weather is not a major contributing cause of work zone crashes in Illinois.

4.3 CORRELATION ANALYSIS OF WORK ZONE CONTRIBUTING CAUSES

Statistical analysis is used in this study to test the association and potential correlation among work zone parameters. Two statistical tests for independence were used in this study: Pearson chi-square, and likelihood-ratio chi-square. Both tests were used to identify whether a pair of factors are correlated or not. The following provide a brief description of these two statistical tests:

4.3.1 Correlation Tests

1- The Pearson Chi-Square Test

The Pearson chi-square test originally proposed by Karl Pearson is widely used for testing the differences between the observed and expected frequencies, where the expected frequencies are computed under the null hypothesis of independence (Bai and Li 2006). To simplify the statistical method used, assume that the observations of crash records are classified by two factors X and Y that are mutually independent and having x and y values respectively. Let x_{ij} be the frequency of a result associated with both factors X_i and Y_j where $x_i = \sum_j x_{ij}$ and $x_j = \sum_i x_{ij}$. Let $n_i \, and \, n_j$ are number of observations in class i, and class j respectively for $i =$ 1, 2,….C and $j =$ 1, 2, …R. For that let

$$e_{ij} = \frac{n_i . n_j}{n} \quad (4.1)$$

and the chi-square statistic is computed as:

$$Q_P = \sum_i \sum_j \frac{(n_{ij} - e_{ij})^2}{e_{ij}} \quad (4.2)$$

Where,

Where Q has an approximate chi-square distribution with (C-1)(R-1) degrees of freedom (SAS Institute Inc. 2006).

2- Likelihood-Ratio Chi-Square Test

The likelihood-ratio chi-square test involves the ratios between the observed frequencies n_{ij} and expected frequencies e_{ij} . Utilizing the same assumption discussed in the previous test, the Likelihood-Ratio Chi-Square test is computed as:

$$G^2 = 2\sum_i \sum_j n_{ij} \ \ln(\frac{n_{ij}}{e_{ij}}) \tag{4.3}$$

Where G^2 has an approximate chi-square distribution with (C-1)(R-1) degrees of freedom (SAS Institute Inc. 2006).

Now to test the independence between factor X and factor Y, the null hypothesis H_0 and the alternative hypothesis H_1 are:

H_0: $P\left(X_i \cap \ Y_j\right) = P(X_i)P\left(Y_j\right)$, or factor X and factor Y are independent; (4.4)

H_1: $P\left(X_i \cap \ Y_j\right) \neq P(X_i)P\left(Y_j\right)$, or factor X and factor Y are not independent (4.5)

Where,

$P\left(X_i \ \ \cap \ Y_j\right)$ is the probability of having X_i and Y_j simultaneously. $P(X_i)$ and $P\left(Y_j\right)$ are the probabilities of having X_i and Y_j, respectively.

Each Factor contributing to the injury and fatal work zone crashes was tested against all other factors. The p-values for both statistical tests were calculated to test whether a null hypothesis could be accepted or not, and for a particular level of significance such as 5%, if p-value is larger than or equal to 0.05, the null hypothesis H_0 will be considered and the two factors are not correlated. If the p-value is less than 0.05, the alternative hypothesis H_1 will be considered and the two factors are correlated. The two statistical tests were performed for identifying all possible correlations and a dependent relationship was determined if both tests supported it (i.e., p-value < 0.05). The test results and the correlated crash factors are discussed in the following section.

4.3.2 Correlation Results of Work Zone Parameters

The aforementioned two correlation tests were performed to evaluate and identify all possible correlations among work zone crash variables that are available in the analyzed HSIS database. Nine variables out of the 31 available HSIS crash variables that are listed in Table 3.8 were excluded from the correlation analysis because of the reasons listed in Table 4.4. All possible correlations among the remaining 22 HSIS variables were evaluated using the aforementioned two correlation tests and the results of this comprehensive analysis are summarized in Table 4.5. A more detailed and focused analysis of these comprehensive correlation results was then conducted to investigate the impact of all the analyzed 22 HSIS variables on four critical crash variables that represent the severity and reported causes of the crash, namely: (1) injury-severity; (2) total injured; (3) number of vehicles; and (4) crash cause. This detailed analysis focused on 26 important correlations that provide useful information on the probable causes that affect the severity of work zone crashes, as shown in Table 4.6 and in the highlighted green cells in Table 4.5. The remaining 92 correlations (see the yellow cells in Table 4.5) do not provide useful information on the impact of work zone parameters on the frequency and severity of crashes. These 92 correlations do not add value to the current analysis as they confirm expected associations between (1) road variables such as the Annual Average Daily Traffic (AADT) and speed limit, and median type and median width; (2) crash variables such as number of vehicles and total injured; or (2) various variables such as the type of collision and the number of lanes, as indicated by the yellow cells in Table 4.5. For each of the identified 26 important correlations in Table 4.6, more detailed analysis was performed and summarized in the following sections of this Chapter.

Table 4.4 Excluded Variables from the Correlation Analysis

Variables	**Reason**
CaseNumber	Unique number identifying each crash record
AccYear	Constant variable
Severity	Redundant as Injury Severity
TotalKilled	Most crash records had zero values
Cause2	Most crash records had zero values
RoadClassification	Redundant as RoutePrefix was used
ClassTrafficway	Redundant as RoutePrefix was used
MultipleDailyVolume	Redundant as AADT was used
MilVehMiTrv	Redundant as AADT was used

Table 4.5 Correlation Matrix for the Analyzed 22 HSIS Variables

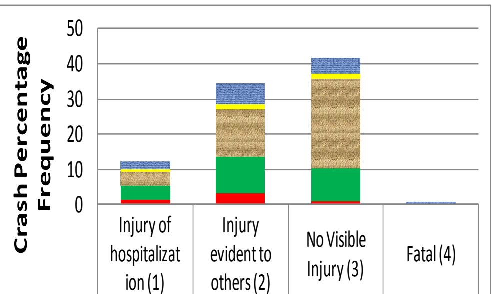
	Acc Hour	Injury-Severity	Total-Injured	Type-Collision	Number-Vehicles	Cause1	Traffic-ContType	TrafficCont-Condition	Route-Prefix	Oneway-Indicator	Intersection-Rel	Type-Construction	Number-Lanes	Surface-Type	Road- Surface Cond	Median-Type	Median-Width	AADT	Commercial-Volume	Speed-Limit	Light	Weather
AccHour	-	N	N	Y	Y	Y	Y	N	Y	N	N	N	Y	N	N	Y	N	Y	Y	N	Y	N
Injury- Severity		-	Y	Y	Y	Y	N	N	N	N	N	N	N	Y	N	Y	N	N	N	Y	N	N
Total- Injured			-	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Type- Collision				-	Y	Y	Y	Y	Y	N	N	N	Y	Y	N	Y	N	Y	N	Y	N	N
Number-Vehicles					-	Y	Y	N	Y	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	N
Cause1						-	Y	Y	Y	N	Y	N	Y	Y	N	Y	Y	Y	Y	Y	Y	N
Traffic- ContType							-	Y	Y	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
TrafficCont-Condition								-	Y	N	Y	N	N	N	N	Y	N	Y	Y	Y	N	Y
Route- Prefix									-	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
Oneway- Indicator										-	Y	N	Y	Y	N	Y	Y	Y	Y	Y	N	N
Intersection- Rel											-	N	Y	Y	N	Y	Y	Y	Y	Y	Y	N
Type- Construction												-	N	N	N	N	N	Y	N	N	N	N
Number- Lanes													-	Y	N	Y	N	Y	Y	Y	Y	N
Surface- Type														-	N	Y	Y	Y	Y	Y	N	N
Road- SurfaceCond															-	N	N	N	N	N	N	Y
Median- Type																-	Y	Y	Y	Y	Y	N
Median- Width																	-	Y	Y	Y	Y	N
AADT																		-	Y	Y	Y	N
Commercial- Volume																			-	Y	Y	N
Speed- Limit																				-	N	N
Light																					-	N
Weather																						-

Table 4.6 Identified 26 Correlations that Affect Crash Severity and Causes

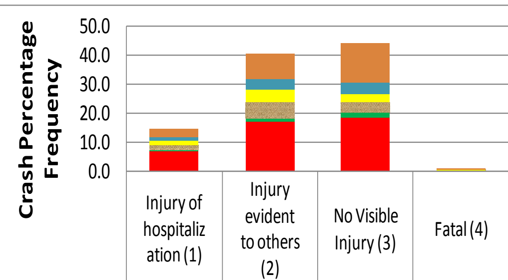
Correlated Crash Factors		Pearson Chi-Square		Likelihood Ratio Chi-Square	
		P-Value	Related	P-Value	Related
1- Injury Severity	Type of Collision	<0.0001	YES	<0.0001	YES
2- Injury Severity	Contributing Cause	<0.0001	YES	<0.0001	YES
3- Injury Severity	Median Type	0.039	YES	0.0324	YES
4- Injury Severity	Speed	0.052	YES	0.04	YES
5- Number of Vehicles	AccHour	<0.0001	YES	<0.0001	YES
6- Number of Vehicles	Type of Collision	<0.0001	YES	<0.0001	YES
7- Number of Vehicles	Contributing Cause	<0.0001	YES	<0.0001	YES
8- Number of Vehicles	Traffic Control Type	<0.0001	YES	<0.0001	YES
9- Number of Vehicles	Route Prefix	<0.0001	YES	<0.0001	YES
10-Number of Vehicles	Median Type	<0.0001	YES	<0.0001	YES
11-Number of Vehicles	AADT	0.0001	YES	0.0005	YES
12-Number of Vehicles	Commercial Volume	<0.0001	YES	0.0003	YES
13-Number of Vehicles	Speed Limit	<0.0001	YES	<0.0001	YES
14-Number of Vehicles	Light Conditions	<0.0001	YES	<0.0001	YES
15-Contributing Cause	AccHour	0.0004	YES	0.0006	YES
16-Contributing Cause	Type of Collision	<0.0001	YES	<0.0001	YES
17-Contributing Cause	Traffic Control Type	<0.0001	YES	<0.0001	YES
18-Contributing Cause	Traffic Control Condition	<0.0001	YES	<0.0001	YES
19-Contributing Cause	Route Prefix	<0.0001	YES	<0.0001	YES
20-Contributing Cause	Intersection Related	<0.0001	YES	<0.0001	YES
21-Contributing Cause	Number of Lanes	<0.0001	YES	<0.0001	YES
22-Contributing Cause	Median Type	<0.0001	YES	<0.0001	YES
23-Contributing Cause	AADT	<0.0001	YES	<0.0001	YES
24-Contributing Cause	Commercial Volume	<0.0001	YES	<0.0001	YES
25-Contributing Cause	Speed	<0.0001	YES	<0.0001	YES
26-Contributing Cause	Light	0.0084	YES	0.0170	YES

4.3.3 Injury Severity Characteristics

The results of the correlation analysis show that the severity of work zone injuries is correlated with 4 parameters; (1) the type of collision; (2) contributing cause; (3) median type; and (4) speed limit as shown in Table 4.6. Different collision types tended to cause different degrees of injury severity, as shown in Figure 4.10(a). The majority of rear-end crashes had only complaints with no visible injury while the majority of other collision types such as angle and fixed object crashes produced visible injuries rather than complaints of pain. A detailed analysis of the correlation between injury severity and crash contributing causes indicated that speed was the dominant contributing cause of fatal crashes while improper driving was the leading cause of injury crashes, as shown in Figure 4.10(b). The results also show that the top three causes of injury crashes were improper driving, speed and work zone environment. As shown in Figure 4.10(c), 30% of fatal crashes occurred in roadways that had no medians while no fatal crashes occurred in roads with rumble strips and painted medians. The results also show that more than 50% of injury crashes occurred on roadways that had no medians or curbed medians. An in-depth analysis of the correlation between injury severity and speed limit indicated that more than 50% of fatal work zone crashes occurred in roads that have a speed limit of 50 mph or higher as shown in Figure 4.10 (d). In roads with a speed limit higher than 50 mph, more than 70% of work zone crashes had evident injuries while that percentage dropped to 57% in roads with lower speed limits. This confirms that injuries sustained in work zone crashes are more severe in roads that have higher speed limits.

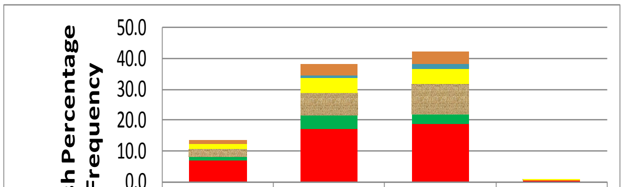


	Injury of hospitalization (1)	Injury evident to others (2)	No Visible Injury (3)	Fatal (4)
Angle (15)	2.4	5.8	4.2	0.3
Sideswipe Same Direction (12)	0.6	1.4	1.6	0
Rear-end (11)	3.9	13.5	25.4	0.2
Turning (10)	4.2	10.4	9.1	0.1
Fixed object (6)	1.3	3.4	1.2	0.1

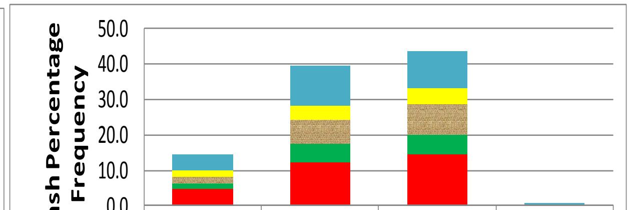


	Injury of hospitalization (1)	Injury evident to others (2)	No Visible Injury (3)	Fatal (4)
Speed(6)	2.7	8.7	13.5	0.3
Unknown(5)	1.3	3.8	4.0	0.1
Traffic Control(4)	1.7	4.3	2.8	0.2
Work Zone Environment(3)	1.7	5.6	3.6	0.1
Distraction(2)	0.2	1.1	1.7	0.0
Improper Driving(1)	7.1	17.1	18.6	0.2

(a) Figure 4.10 (b)



	Injury of hospitalization (1)	Injury evident to others (2)	No Visible Injury (3)	Fatal (4)
Pained (5)	1.2	3.6	4.2	0.0
Rumble Strip (4)	0.1	0.8	1.7	0.0
Positive Barrier (3)	1.4	4.9	4.7	0.1
Curbed (2)	2.4	7.3	9.8	0.1
Unprotected (1)	1.4	4.5	3.4	0.2
No Median (0)	6.9	17.0	18.5	0.3



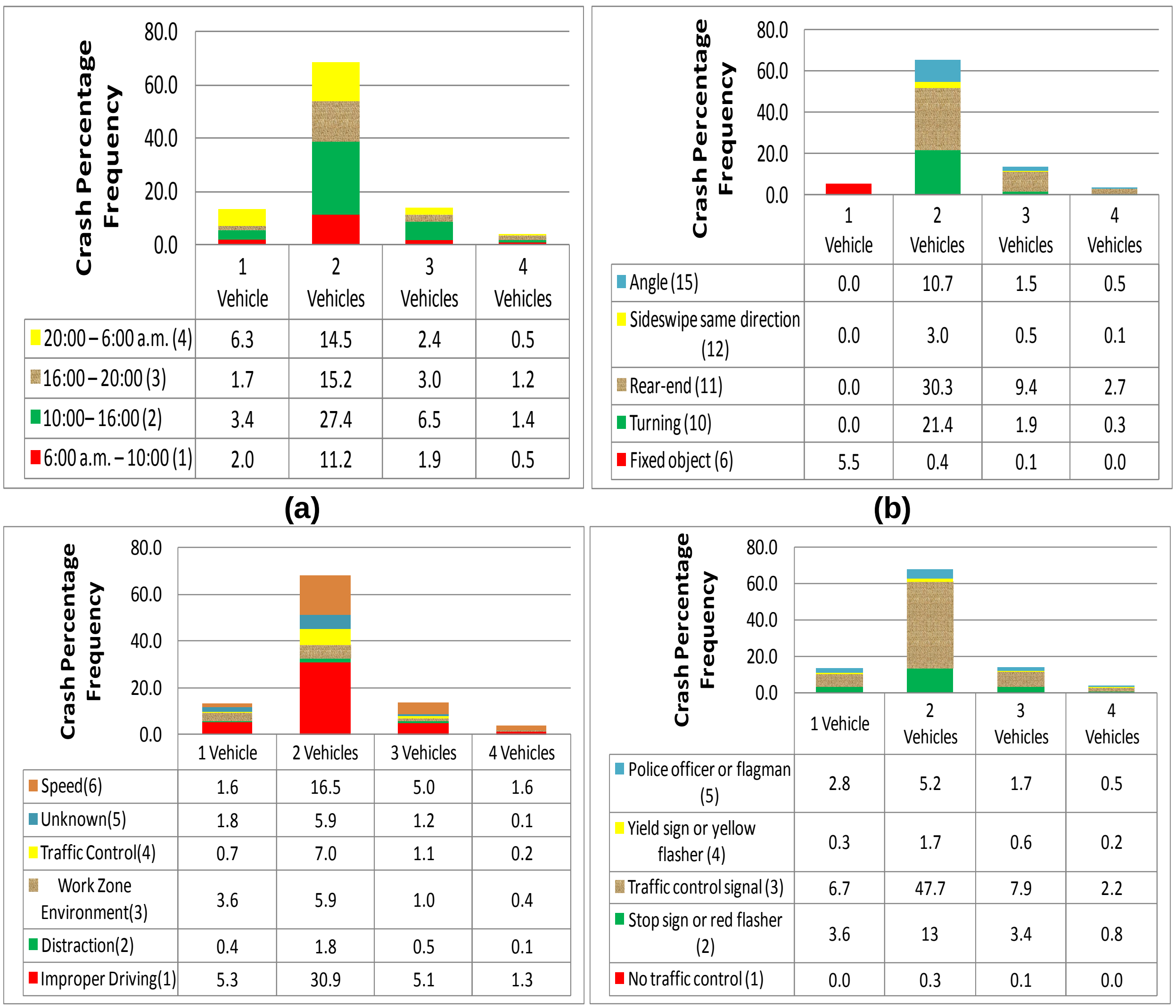
	Injury of hospitalization (1)	Injury evident to others (2)	No Visible Injury (3)	Fatal (4)
over 55 mph	4.3	11.5	10.2	0.4
50 mph	2	4	4.5	0.1
45 mph	1.7	6.5	8.6	0.2
40 mph	1.7	5.4	5.6	0.1
below 35 mph	4.8	12.2	14.5	0.0

(c) **(d)**

Figure 4.10 Crash frequency percentages by injury severity and (a) the type of collision; (b) contributing cause; (c) median type; and (d) speed limit

4.3.4 Number of Vehicles Involved

The results of the correlation analysis show that the number of vehicles involved in a crash is correlated with 10 work zone parameters; (1) accident hour; (2) type of collision; (3) contributing cause; (4) traffic control type; (5) route prefix; (6) median type; (7) AADT; (8) commercial volume; (9) speed limit; and (10) light condition. The analysis of the correlation dependency between number of vehicles involved and the accident hour indicates that crashes that involved one vehicle were more likely to occur during the nighttime period (20:00 – 6 am) while crashes that involved two vehicles were more prone to occur at non-peak morning period (10:00am – 4:00pm), as shown in Figure 4.11(a). The number of vehicles involved in a crash is correlated with the type of collision. As shown in Figure 4.11(b), rear-end and turning crashes that involved two vehicles represent more than 50% of the overall work zone injury and fatal crashes and fixed object collisions are the leading type of crashes involving one vehicle only, while rear end collisions are the leading type of crashes involving 3 vehicles or more. The leading two causes of crashes involving only one vehicle were improper driving and work zone environment that caused 66% of this type of crashes as shown in Figure 4.11(c). For crashes involving two vehicles or more, the leading two causes of crashes were improper driving and speed that resulted in approximately 70% of this type of crashes. As for traffic control type, Figure 4.11(d) shows that only 2.8% of total work zone crashes occurred when a yellow flasher was in use compared to 10.2% when a police officer or flagman was on site.



	1 Vehicle	2 Vehicles	3 Vehicles	4 Vehicles
20:00 – 6:00 a.m. (4)	6.3	14.5	2.4	0.5
16:00 – 20:00 (3)	1.7	15.2	3.0	1.2
10:00– 16:00 (2)	3.4	27.4	6.5	1.4
6:00 a.m. – 10:00 (1)	2.0	11.2	1.9	0.5

(a)

	1 Vehicle	2 Vehicles	3 Vehicles	4 Vehicles
Angle (15)	0.0	10.7	1.5	0.5
Sideswipe same direction (12)	0.0	3.0	0.5	0.1
Rear-end (11)	0.0	30.3	9.4	2.7
Turning (10)	0.0	21.4	1.9	0.3
Fixed object (6)	5.5	0.4	0.1	0.0

(b)

	1 Vehicle	2 Vehicles	3 Vehicles	4 Vehicles
Speed(6)	1.6	16.5	5.0	1.6
Unknown(5)	1.8	5.9	1.2	0.1
Traffic Control(4)	0.7	7.0	1.1	0.2
Work Zone Environment(3)	3.6	5.9	1.0	0.4
Distraction(2)	0.4	1.8	0.5	0.1
Improper Driving(1)	5.3	30.9	5.1	1.3

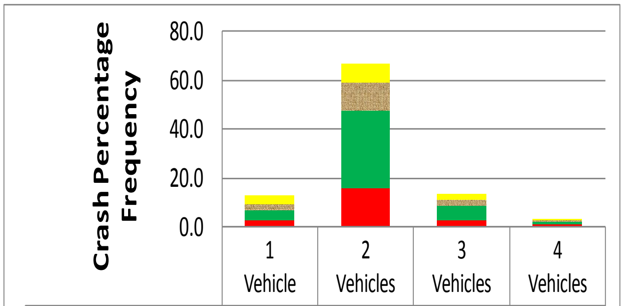
(c)

	1 Vehicle	2 Vehicles	3 Vehicles	4 Vehicles
Police officer or flagman (5)	2.8	5.2	1.7	0.5
Yield sign or yellow flasher (4)	0.3	1.7	0.6	0.2
Traffic control signal (3)	6.7	47.7	7.9	2.2
Stop sign or red flasher (2)	3.6	13	3.4	0.8
No traffic control (1)	0.0	0.3	0.1	0.0

(d)

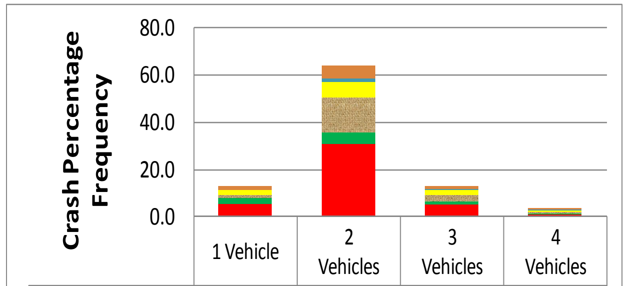
Figure 4.11 Crash frequency percentages by number of vehicles involved and (a) accident hour; (b) type of collision; (c) contributing cause; and (d) traffic control type

The number of vehicles involved in a crash was found to be statistically correlated with the type of route. As shown in Figure 4.12(a), crashes involving two vehicles represent 67% of total crashes and almost half of these crashes occurred on Illinois routes. The results also show that the top three types of routes that had one vehicle crashes were Illinois routes, interstate routes, and U.S. routes, while the top three routes that had crashes involving two vehicles were Illinois routes, U.S. routes, and State maintained routes. As shown in Figure 4.12(b), 45% of work zone crashes that involved two vehicles occurred on roads that had no medians while roads with rumble strips had the least percentage of work zone crashes. Almost half of work zone crashes occurred on roads that had no medians. The number of vehicles involved in a crash was found to be statistically related to the Annual Average Daily Traffic (AADT) of the road. As shown in Figure 4.12(c), the highest rate of work zone crashes occurred on roads with AADT that ranges from 10,000 to 20,000. Beyond that peak range, the rate of work zone crashes tends to gradually decrease in roads with higher ranges of AADT. Similarly, the majority of work zone crashes occurred in roads with commercial volume below 2000 as shown in Figure 4.12(d) while the rate of work zone crashes tends to gradually decrease as the commercial volume of the road increases.



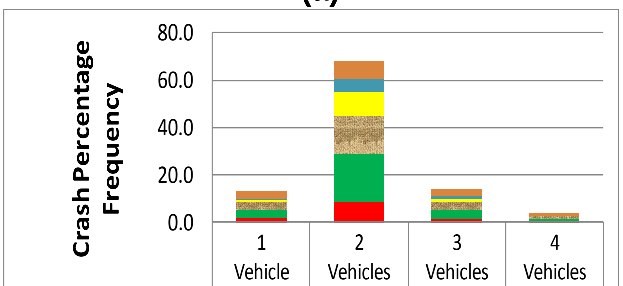
	1 Vehicle	2 Vehicles	3 Vehicles	4 Vehicles
Intersate Route (9)	4.0	7.7	2.6	0.7
State Maintained Route (8)	2.4	11.4	1.9	0.8
Illinois Route (5)	4.2	31.4	6.4	1.3
U.S. Route (1)	2.6	16.1	2.7	0.8

(a)



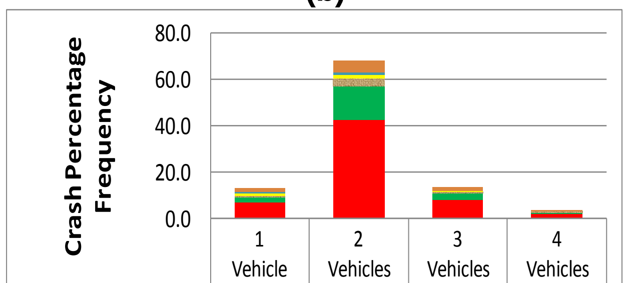
	1 Vehicle	2 Vehicles	3 Vehicles	4 Vehicles
Pained (5)	1.7	5.5	1.2	0.5
Rumble Strip (4)	0.1	1.8	0.5	0.2
Positive Barrier (3)	2.3	6.4	1.9	0.5
Curbed (2)	1	14.9	2.8	0.8
Unprotected (1)	2.8	5.0	1.4	0.3
No Median (0)	5.2	30.8	5.2	1.2

(b)



	1 Vehicle	2 Vehicles	3 Vehicles	4 Vehicles
Over than 50,000 (6)	3.2	7.5	2.4	0.8
40,000 ~ 50,000 (5)	0.7	5.5	1.1	0.2
30,000 ~ 40000 (4)	1	10.4	1.9	0.3
20,000~30,000 (3)	3.3	16.1	3.4	0.8
10,000 ~ 20,000 (2)	3.3	20.4	3.5	1.3
Below 10,000 (1)	2.0	8.3	1.6	0.3

(c)

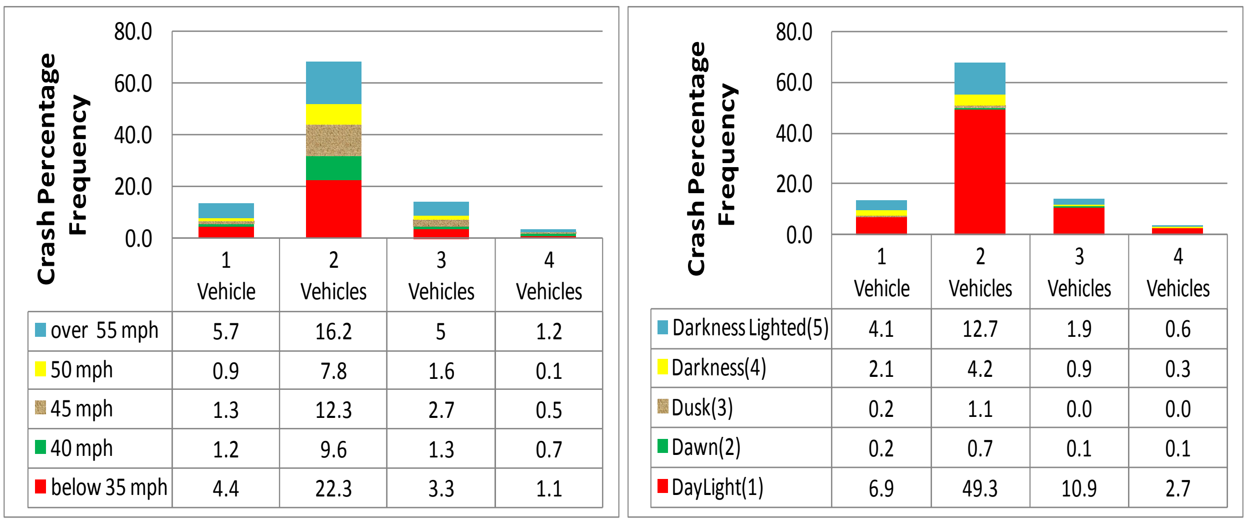


	1 Vehicle	2 Vehicles	3 Vehicles	4 Vehicles
Over than 10000 (6)	1.9	5.3	1.6	0.5
8000 ~ 10000 (5)	0.3	0.8	0.1	0
6000 ~ 8000 (4)	1.3	1.7	0.4	0.2
4000 ~ 6000 (3)	0.5	3.4	0.8	0.2
2000 ~ 4000 (2)	2.4	14.4	2.8	0.9
Below 2000 (1)	7.1	42.7	8.1	1.9

(d)

Figure 4.12 Crash frequency percentages by number of vehicles involved and (a) route prefix; (b) median type; (c) AADT; and (d) commercial volume

The speed limit of 55 mph experienced the highest rate of work zone crashes while the majority of these crashes involved two vehicles (see Figure 4.13(a)). The results also show that crash rates gradually increased as the speed limit of the road increased from 35 mph until 45 mph followed by a drop in these rates at the 50 mph speed limit and then they reversed course and reached a peak at the 55 mph speed limit, as shown in Figure 4.13(a). As for the light condition, Figure 4.13(b) presents the injury and fatal work zone crash frequencies categorized by light conditions and number of vehicles involved. The results show that 51% of one vehicle crashes and 26% of two vehicle crashes occurred during nighttime work zones when the lighting conditions were reported to be darkness, dawn or dusk. Considering the fact that the total number of vehicles that drive by nighttime work zones is much less than those in daytime work zones, these percentages suggest that the rate of crashes per 1000 vehicles that drive by work zones is higher during nighttime construction.



	1 Vehicle	2 Vehicles	3 Vehicles	4 Vehicles
over 55 mph	5.7	16.2	5	1.2
50 mph	0.9	7.8	1.6	0.1
45 mph	1.3	12.3	2.7	0.5
40 mph	1.2	9.6	1.3	0.7
below 35 mph	4.4	22.3	3.3	1.1

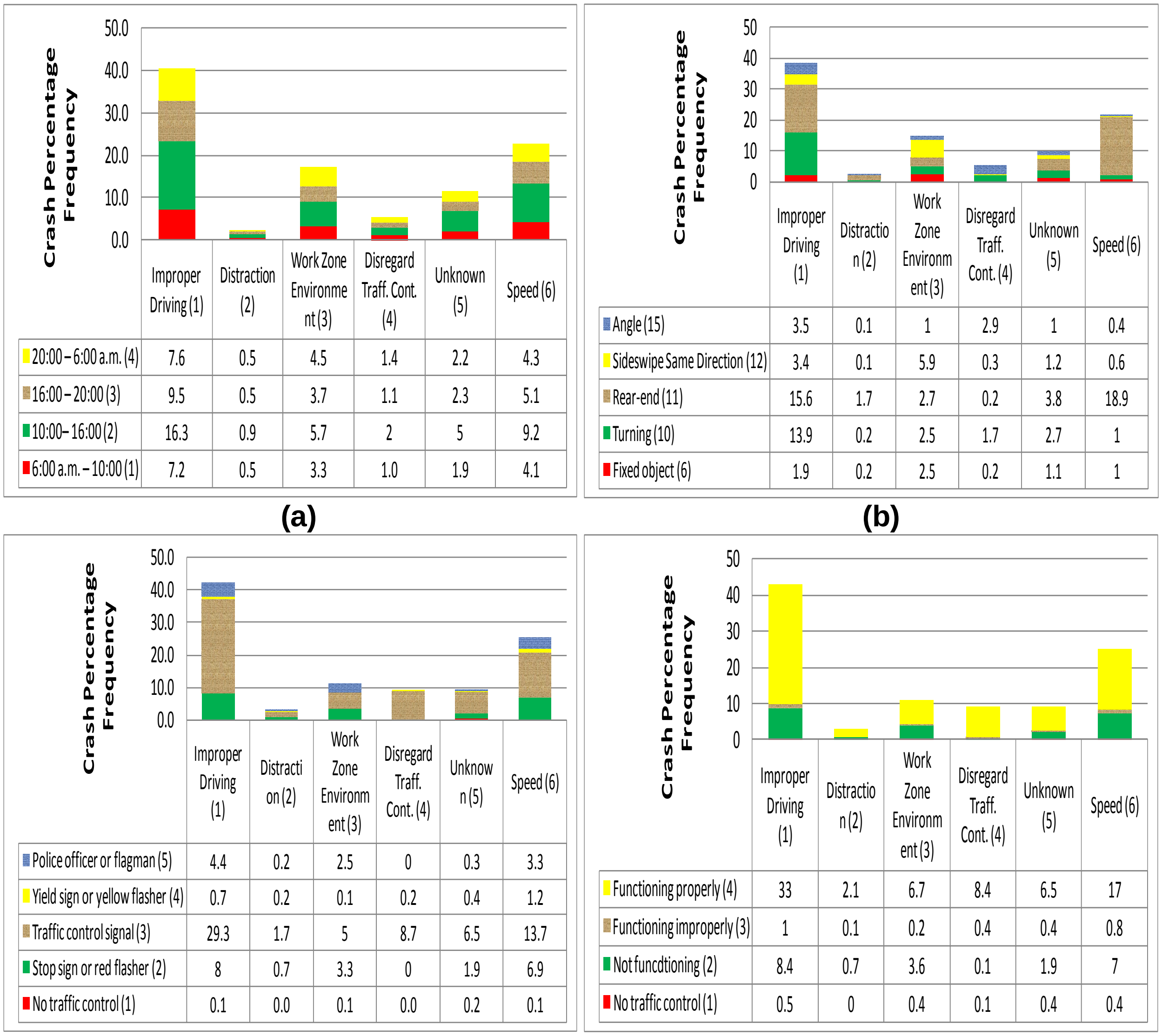
	1 Vehicle	2 Vehicles	3 Vehicles	4 Vehicles
Darkness Lighted(5)	4.1	12.7	1.9	0.6
Darkness(4)	2.1	4.2	0.9	0.3
Dusk(3)	0.2	1.1	0.0	0.0
Dawn(2)	0.2	0.7	0.1	0.1
DayLight(1)	6.9	49.3	10.9	2.7

(a) **(b)**

Figure 4.13 Crash frequency percentages by number of vehicles involved and (a) speed limit; and (b) light condition

4.3.5 Contributing Causes of Work Zone Crashes

The correlation analysis results show that the contributing cause of work zone crashes is correlated with 14 work zone parameters; (1) accident hour; (2) type of collision; (3) traffic control type; (4) traffic control condition; (5) route prefix; (6) intersection relevance; (7) number of lanes; (8) median type; (9) AADT; (10) commercial volume; (11) speed limit; and (12) light condition. Figure 4.14(a) shows that the top two causes of crashes during the three daytime periods from 6 am to 8 pm were improper driving and speed, while the top two causes of crashes during the nighttime period from 8 pm to 6 am were improper driving and work zone environment. The relative significance of work zone environment during the nighttime period suggests that work zone parameters including lighting conditions have an important impact on the frequency of nighttime work zone crashes. The contributing cause of the crash was found to be statistically correlated with the type of collision. As shown in Figure 4.14(b), 44% of rear-end crashes were caused by speed while 64% of turning crashes were caused by improper driving. Work zone environment was reported to be the cause of more than 50% of sideswipes same direction collisions and 36% of fixed object collisions. Figure 4.14(c) presents the crash percentage frequency of contributing causes and traffic control type. Improper driving was the most reported cause of work zone crashes followed by speed. This analysis also shows that 69% of the crashes that were caused by improper driving and 54% of crashes that were caused by speed occurred on roads that had regular traffic control signals. The two traffic control measures that had the least rates of work zone crashes were (a) yield sign or yellow flasher; and (b) police officer or flagman. As for the condition of traffic control countermeasures, Figure 4.14(d) shows that the condition was not a major cause of work zone crashes since 73.7% of work zone crashes occurred when the traffic control was functioning properly.



(a)

	Improper Driving (1)	Distraction (2)	Work Zone Environment (3)	Disregard Traff. Cont. (4)	Unknown (5)	Speed (6)
20:00 – 6:00 a.m. (4)	7.6	0.5	4.5	1.4	2.2	4.3
16:00 – 20:00 (3)	9.5	0.5	3.7	1.1	2.3	5.1
10:00– 16:00 (2)	16.3	0.9	5.7	2	5	9.2
6:00 a.m. – 10:00 (1)	7.2	0.5	3.3	1.0	1.9	4.1

(b)

	Improper Driving (1)	Distraction (2)	Work Zone Environment (3)	Disregard Traff. Cont. (4)	Unknown (5)	Speed (6)
Angle (15)	3.5	0.1	1	2.9	1	0.4
Sideswipe Same Direction (12)	3.4	0.1	5.9	0.3	1.2	0.6
Rear-end (11)	15.6	1.7	2.7	0.2	3.8	18.9
Turning (10)	13.9	0.2	2.5	1.7	2.7	1
Fixed object (6)	1.9	0.2	2.5	0.2	1.1	1

(c)

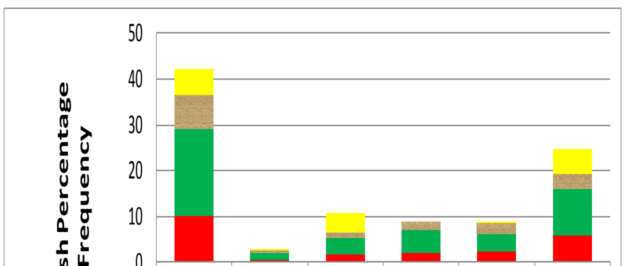
	Improper Driving (1)	Distraction (2)	Work Zone Environment (3)	Disregard Traff. Cont. (4)	Unknown (5)	Speed (6)
Police officer or flagman (5)	4.4	0.2	2.5	0	0.3	3.3
Yield sign or yellow flasher (4)	0.7	0.2	0.1	0.2	0.4	1.2
Traffic control signal (3)	29.3	1.7	5	8.7	6.5	13.7
Stop sign or red flasher (2)	8	0.7	3.3	0	1.9	6.9
No traffic control (1)	0.1	0.0	0.1	0.0	0.2	0.1

(d)

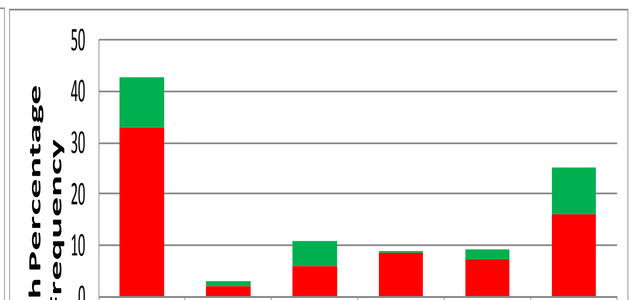
	Improper Driving (1)	Distraction (2)	Work Zone Environment (3)	Disregard Traff. Cont. (4)	Unknown (5)	Speed (6)
Functioning properly (4)	33	2.1	6.7	8.4	6.5	17
Functioning improperly (3)	1	0.1	0.2	0.4	0.4	0.8
Not funcdtioning (2)	8.4	0.7	3.6	0.1	1.9	7
No traffic control (1)	0.5	0	0.4	0.1	0.4	0.4

Figure 4.14 Crash frequency percentages by contributing cause and (a) accident hour; (b) type of collision; (c) traffic control type; and (d) traffic control condition

The contributing cause of the crash was found to be statistically correlated with the type of route. As shown in Figure 4.15(a), 44% of work zone crashes that were caused by improper driving occurred on Illinois routes while 38% of work zone crashes that were caused by work zone environment occurred on interstate routes. As shown in Figure 4.15(b), the contributing cause of work zone crashes was related to whether work zone is in intersection or not. Generally, intersection crashes represented 72.7% of the total crashes and the top two leading causes for these crashes were improper driving and speed. The number of lanes of a roadway affects the contributing cause of work zone crashes. As shown in Figure 4.15(c), the majority of work zone crashes (55.7%) occurred on 4-lane roads and the majority caused due to improper driving. However, highways of 8 lanes speed and improper driving are the leading contributing causes of crashes. The median type of the road was found statistically correlated with the contributing cause of a crash. As shown in Figure 4.15(d), work zone crashes caused by improper driving were more prone to occur in roads that had no medians or had curbed medians. The results show that 32% of crashes that were caused due to work zone environment occurred on roads with no median and only 2% of this type crashes occurred on roads with rumble strips. The results also show that the two types of median that had the least number of reported crashes were rumble strips and mountable median.

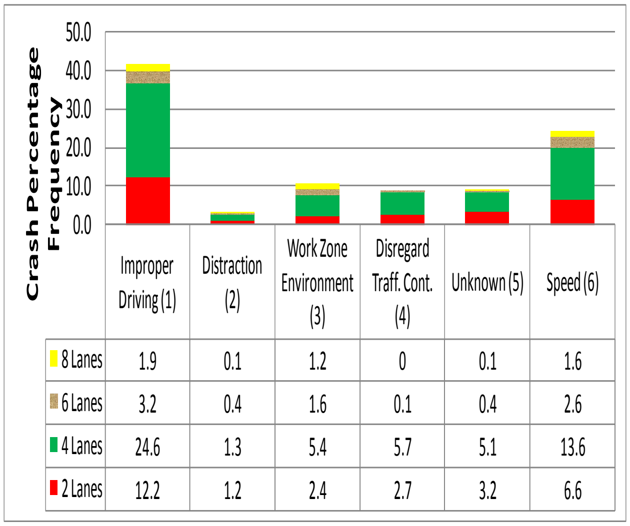


	Improper Driving (1)	Distraction (2)	Work Zone Environment (3)	Disregard Traff. Cont. (4)	Unknown (5)	Speed (6)
Interstate (9)	5.6	0.3	4.1	0	0.4	5.3
Non-marked route (8)	7.4	0.5	1.3	1.7	2.4	3.3
Illinois route (5)	19.1	1.5	3.5	4.9	3.8	10.2
U.S. route (1)	10.1	0.6	1.7	2.1	2.3	5.8



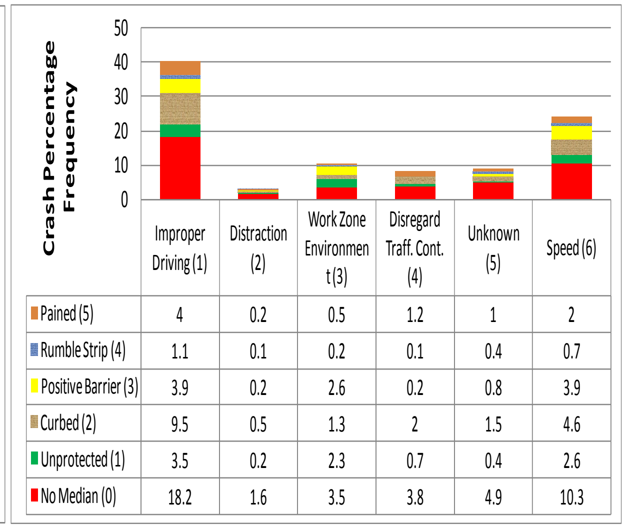
	Improper Driving (1)	Distraction (2)	Work Zone Environment (3)	Disregard Traff. Cont. (4)	Unknown (5)	Speed (6)
No (2)	9.8	0.9	5.1	0.2	2.1	9.1
Yes (1)	33.1	2	5.8	8.7	7.1	16

(a) **Figure 4.15** **(b)**



	Improper Driving (1)	Distraction (2)	Work Zone Environment (3)	Disregard Traff. Cont. (4)	Unknown (5)	Speed (6)
8 Lanes	1.9	0.1	1.2	0	0.1	1.6
6 Lanes	3.2	0.4	1.6	0.1	0.4	2.6
4 Lanes	24.6	1.3	5.4	5.7	5.1	13.6
2 Lanes	12.2	1.2	2.4	2.7	3.2	6.6

(c)

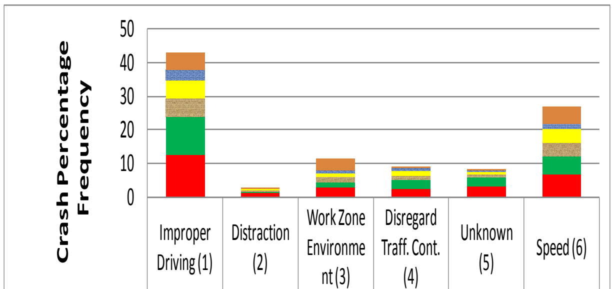


	Improper Driving (1)	Distraction (2)	Work Zone Environmen t (3)	Disregard Traff. Cont. (4)	Unknown (5)	Speed (6)
Pained (5)	4	0.2	0.5	1.2	1	2
Rumble Strip (4)	1.1	0.1	0.2	0.1	0.4	0.7
Positive Barrier (3)	3.9	0.2	2.6	0.2	0.8	3.9
Curbed (2)	9.5	0.5	1.3	2	1.5	4.6
Unprotected (1)	3.5	0.2	2.3	0.7	0.4	2.6
No Median (0)	18.2	1.6	3.5	3.8	4.9	10.3

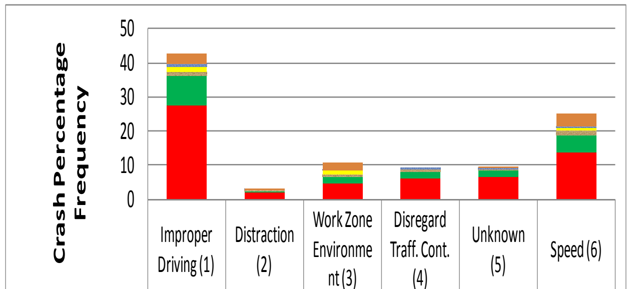
(d)

Figure 4.15 Crash frequency percentages by contributing cause and (a) route prefix; (b) intersection relevance; (c) number of lanes; and (d) median type

The contributing cause of work zone crashes was found to be statistically correlated with the Annual Average Daily Traffic (AADT) of the road. Figure 4.16(a) shows a steady decrease in crashes caused by improper driving as the AADT of the road increases. This suggests that drivers tend to be more cautious in heavy traffic conditions. On the other hand, the risk of crashes that are caused by work zone environment increased in heavy traffic roads with AADT exceeding 50,000. Similarly, Figure 4.16(b) shows a steady decrease in crashes caused by improper driving as the commercial volume of the road increases. Once more, this suggests that drivers tend to be more cautious in heavy commercial traffic conditions. On the other hand, the risk of crashes that are caused by work zone environment increased in heavy traffic roads with commercial volume exceeding 10,000. The statistical analysis of dependence show that the contributing cause of work zone crashes was related to the speed limit of the road. As shown in Figure 4.16(c), more than 50% of the crashes that were caused by work zone environment occurred in roads with speed limits that are higher than 50 mph compared to 31% for the crashes that were caused by improper driving in roads with the same speed limits. The light condition of the road during the time of crash was correlated with the contributing cause of work zone crashes. Figure 4.16(d) presents the injury and fatal work zone crash frequencies categorized by light conditions and contributing causes. The results show that 40% of work zone environment crashes and approximately 30% of the remaining types of crashes occurred in nighttime work zones during darkness, dawn or dusk. Taking into consideration the fact that the total number of vehicles that drive by nighttime work zones is much less than those in daytime work zones, these percentages confirm that the rate of crashes per 1000 vehicles that drive by work zones is higher during nighttime construction.

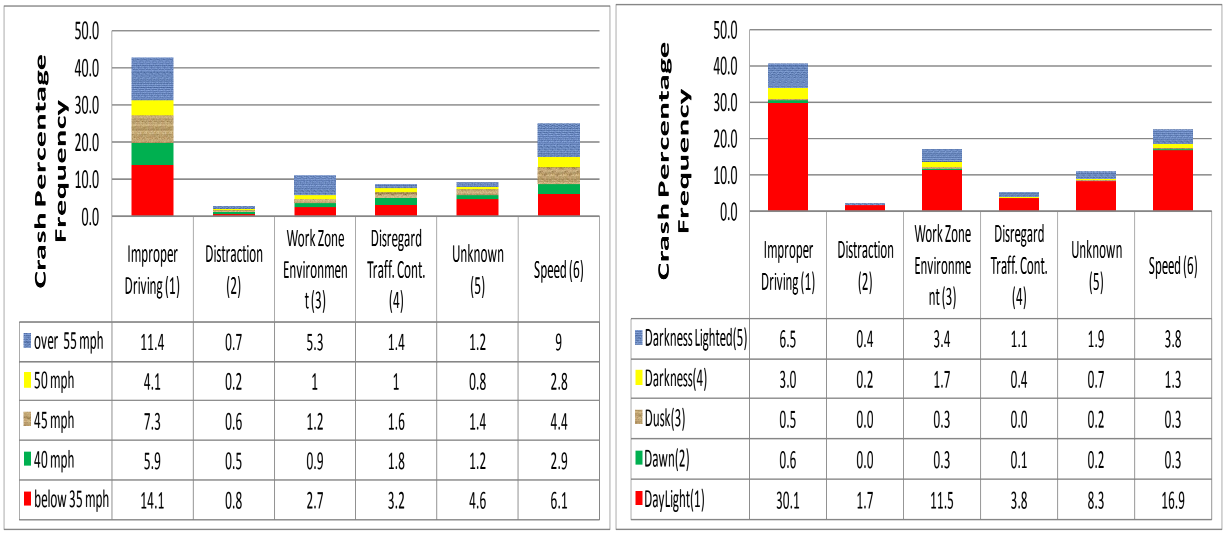


	Improper Driving (1)	Distraction (2)	Work Zone Environment (3)	Disregard Traff. Cont. (4)	Unknown (5)	Speed (6)
Over than 50,000 (6)	5.4	0.4	3.3	0.1	0.4	4.9
40,000~50,000 (5)	3	0.2	0.7	0.7	0.7	1.7
30,000~40000 (4)	5.4	0.3	1.4	1.3	0.8	4.1
20,000~30,000 (3)	5.4	0.3	1.4	1.3	0.8	4.1
10,000~20,000 (2)	11.5	0.5	1.7	2.6	2.4	5.2
Below 10,000 (1)	12.4	1.2	2.7	2.6	3.3	6.8



	Improper Driving (1)	Distraction (2)	Work Zone Environment (3)	Disregard Traff. Cont. (4)	Unknown (5)	Speed (6)
Over than 10000 (6)	3.3	0.1	2.4	0	0.2	3.8
8000~10000 (5)	0.5	0.1	0.2	0.1	0.1	0.3
6000~8000 (4)	1.5	0.1	1.2	0.1	0.1	0.7
4000~6000 (3)	1.3	0.2	0.6	0.5	0.2	1.5
2000~4000 (2)	8.8	0.7	1.7	2.1	2.1	5.1
Below 2000 (1)	27.4	1.8	4.8	6.0	6.5	13.7

(a) **Figure 4.16** **(b)**



(c)	Improper Driving (1)	Distraction (2)	Work Zone Environment (3)	Disregard Traff. Cont. (4)	Unknown (5)	Speed (6)
over 55 mph	11.4	0.7	5.3	1.4	1.2	9
50 mph	4.1	0.2	1	1	0.8	2.8
45 mph	7.3	0.6	1.2	1.6	1.4	4.4
40 mph	5.9	0.5	0.9	1.8	1.2	2.9
below 35 mph	14.1	0.8	2.7	3.2	4.6	6.1

(d)	Improper Driving (1)	Distraction (2)	Work Zone Environment (3)	Disregard Traff. Cont. (4)	Unknown (5)	Speed (6)
Darkness Lighted(5)	6.5	0.4	3.4	1.1	1.9	3.8
Darkness(4)	3.0	0.2	1.7	0.4	0.7	1.3
Dusk(3)	0.5	0.0	0.3	0.0	0.2	0.3
Dawn(2)	0.6	0.0	0.3	0.1	0.2	0.3
DayLight(1)	30.1	1.7	11.5	3.8	8.3	16.9

(c) **(d)**

Figure 4.16 Crash frequency percentages by contributing cause and (a) AADT; (b) commercial volume; (c) speed limit; and (d) light condition

4.3.6 Basic Findings of the Correlation Analysis

The correlation analysis in the previous section used the most recent five years (2003-2007) of crash data that were available from the Highway Safety Information System (HSIS). The HSIS data files contained a total of 875,537 records for the state of Illinois during this 5 year period, including 1,729 work zone crash records that represent all recorded injury and fatal work zone crashes. The HSIS crash data were analyzed to investigate and identify correlations among 22 important work zone crash variables that are available in the HSIS database such as crash severity, light conditions, and type of collision. Statistical correlation methods were applied to test all possible and meaningful combinations among these crash variables and 26 important combinations were indentified and further investigated. The main findings of this comprehensive and detailed correlation analysis include:

1- The severity of work zone crashes was found to be correlated with and affected by the type of collision, the drivers' actions that caused the crash, the type of road surface, the type of median and the speed limits of the road.

2- The number of vehicles involved in a work zone crash was found to be correlated with and affected by the crash time, the road lighting conditions, the type of collision, the drivers' actions that caused the crash, the classification of the road, the type and width of the median, the AADT and commercial volume on the road, and the speed limits of the road.

3- The reported drivers' actions that caused work zone crashes was found to be correlated with and affected by the crash time, the road lighting conditions, the type of collision, the classification of the road, the type of road surface, the type and width of the median, the traffic control type and its condition, the number of lanes, the AADT and commercial volume on the road, and the speed limit of the road.

4- The majority of rear-end crashes had only pain complaints with no visible injury while the majority of other collision types such as angle and fixed object crashes produced visible injuries rather than merely complaints.

5- More than 37% of fatal crashes occurred in roadways that had no medians while no fatal crashes occurred in roads with rumble strips and painted medians. The correlation results also show that more than 50% of injury crashes occurred on roadways that had no medians or curbed medians.

6- More than 50% of fatal work zone crashes occurred in roads that have a speed limit of 50 mph or higher.

7- Speed was the dominant contributing cause of fatal work zone crashes while improper driving was the leading cause of injury crashes. The results also show that the top three causes of injury crashes are improper driving, speed and work zone environment.

8- Crashes that involved one vehicle were more likely to occur during the nighttime period (20:00 – 6 am) while crashes that involved two vehicles were more prone to occur at the non-peak morning period (10:00am – 4:00pm).

9- Rear-end and turning crashes that involved two vehicles represent more than 50% of the overall work zone injury and fatal crashes. The results also show that fixed object collisions are the leading type of crashes involving one vehicle only, while rear end collisions are the leading type of crashes involving three vehicles or more.

10- The leading two causes of crashes involving only one vehicle were improper driving and work zone environment that caused 66% of this type of crashes. For crashes involving two vehicles or more, the leading two causes of crashes were improper driving and speed that resulted in approximately 70% of this type of crashes.

11- The majority of work zone crashes occurred when traffic control signals were on site. Only 2.8% of total work zone crashes occurred when a yellow flasher was in use compared to 10.3% when a police officer or flagman was on site.

12- Crashes involving two vehicles represent 68.2% of total work zone crashes and almost half of these crashes occurred on Illinois routes. The results also show that the top three types of routes that had one vehicle crashes were Illinois routes, interstate routes, and U.S. routes, while the top three routes that had crashes involving two vehicles were Illinois routes, U.S. routes, and State maintained routes.

13- The majority of all work zone crashes (59%) occurred on roads that had no medians or medians with a width less than 10 feet.

14- The highest rate of work zone crashes occurred on roads with Annual Average Daily Traffic (AADT) that ranges from 10,000 to 20,000. Beyond that peak range, the rate of work zone crashes tends to gradually decrease in roads with higher ranges of AADT.

15- The majority of work zone crashes occurred in roads with commercial volume below 2000. The rate of work zone crashes tends to gradually decrease as the commercial volume of the road increases.

16- Work zone crash rates gradually increased as the speed limit of the road increased from 20 mph until 45 mph followed by a drop in these rates at the 50 mph speed limit and then they reversed course and reached a peak at the 55 mph speed limit.

17- The majority of one vehicle crashes (51%) and 26% of two vehicle crashes occurred during nighttime work zones when the lighting conditions were reported to be darkness, dawn or dusk. Considering the fact that the total number of vehicles that drive by nighttime work zones is much less than those in daytime work zones, these percentages suggest that the rate of crashes per 1000 vehicles that drive by work zones is higher during nighttime construction.

18- The top two causes of crashes during the daytime periods from 6 am to 8 pm were improper driving and speed, while the top two causes of crashes during the nighttime period from 8 pm to 6 am were improper driving and work zone environment. The relative significance of work zone environment during the nighttime period suggests that work zone parameters including lighting conditions have an important impact on the frequency of nighttime work zone crashes.

19- The majority of turning crashes (64%) were caused by improper driving while 44% of rear-end crashes were caused by speed. Work zone environment was reported to cause more than 50% of sideswipe same direction collisions and 36% of fixed object collisions.

20- The majority of crashes that were caused by improper driving (69%) and speed (54%) occurred on roads that had regular traffic control signals. The two traffic control measures that had the least rates of work zone crashes were (a) yield sign or yellow flasher; and (b) police officer or flagman.

21- The condition of traffic control devices was not a major cause of work zone crashes as 73.7% of these crashes occurred when the traffic control was functioning properly.

22- The two types of road median that had the least number of reported crashes were rumble strips and mountable median. This suggests that these types of medians may contribute to reduce the risks of work zone crashes.

4.4 DEVELOPMENT OF CRASH SEVERITY INDICES

Work zone safety is affected by many work zone parameters. Identifying the risk levels of work zone parameters is a crucial step towards mitigating the occurrence of severe crashes. In this section, six crash severity indices were developed to represent the probability of a work zone to cause severe crashes. The six crash severity indices are grouped in three categories that represent the probability of a work zone to encounter: (1) severe injury crashes; (2) multi-vehicles crashes; and (3) multi-injuries crashes. The six indices are numerical values between zero and one that can be estimated from given work zone characteristics. High values of crash severity indices reflect the high probability of work zones to encounter severe crashes.

Crash severity indices were developed using the logistic regression method to provide straightforward indications of work zone risk levels based on work zone variables that may contribute to the occurrence of severe work zone crashes. Logistic regression models are used for predicting the probability of occurrence of an event by fitting data to a logit function logistic curve as a generalized linear models used for binomial regression (Stokes et al. 2001). These models enforce no requirement on the distributions of the explanatory variables or predictors which make them more flexible and more likely to yield accurate results in traffic crash analyses where the safety impact of contributing factors are quantified (Harrell 2001, Li and Bai 2008). Like many forms of regression analysis, logistic regression is a model whose dependent variables are discrete or categorical such as crash severity indices, and it describes the relationship between this variable and a set of explanatory predictors such as work zone contributing factors no matter whether these predictors are continuous or not (Lu et al. 2006).

For ordinal logistic regression models, the response variable, Y, might be constrained to a number of ordinal values denoted by 1,……, K, K+1 where K is the number of ordinal values of the response variable Y. For example, the severity of a work zone crash is treated as a response variable Y that has three classification (K=3) such that 1= injury other than fatal requiring hospitalization, 2= injury evident to others at scene, and 3= no visible injury. The logistic regression technique fits a common slopes cumulative model based on the cumulative probabilities of the response categories rather than on their individual probabilities (SAS 2003). As shown in equation (eq.4.6), the cumulative model is then has the form

$$g(p_i = \Pr(Y \leq i \setminus x)) = \ln[{}^{p_i}/_{(1 - P_i)}] = \alpha_i + \beta' x \qquad i = 1, \ldots, k \tag{4.6}$$

Where α_1, ….., α_k = k intercept parameters; β' = the vector of slope parameters; and x_i = the vector of explanatory variables. This logistic regression equation models the logit transformation of the i th observation probability, p_i , as a linear function of the explanatory variables in the vector, x_i. For the log odds scale, the cumulative logit model is often referred to as the proportional odds model while the regression coefficients provide estimates of the impact of each independent variable on the odds of the dependent variable (Long 1997).

In this study, six logistic regression models for work zone crash severity were developed based on work zone crash records of the state of Illinois. The proportional odds models were employed to determine the probability of severe work zone crash occurrence given certain traffic operational, geometries, and environmental conditions. The LOGISTIC procedure in SAS 9.2 was used to estimate the model parameters and assess the model goodness-of-fit. The objective of these models is to describe the association between the ordinal response (work zone crash severity) and some explanatory variables (such as trafficway class, route prefix, geometric configurations, and Light condition).

The development and validation of the six crash severity indices were based on Illinois Highway Safety Information System (HSIS) crash dataset that included between 105,000 and 205,000 crashes per year (www.hsisinfo.org). The main reason for choosing HSIS dataset was due to the additional road and traffic data it provided and was not available in the comprehensive National Highway and Traffic Safety Administration data files (Council and Mohamedshah 2009). The crash dataset provided through HSIS for the state of Illinois had a fourth file (Roadlog file) that contains additional data on the road and traffic such as number of lanes, lane width, median type and width, AADT, commercial volume, and speed limit. Injury work zone crashes of HSIS have been extracted for a 5 year period between 2003 and 2007 that included a total of 1714 crashes. Out of these 1714 crash records, 1514 records were used for the development of the models while 200 records were selected randomly for validation and testing. The original format of the data was that a single crash was frequently represented in multiple data rows in multiple crash files depending on the number of vehicles and persons involved. This data format could not be directly utilized for computer-aided- analyses, therefore the format of crash data has been changed using a 5 step procedure as discussed in Chapter 3. A total number of 20 work zone crash variables were considered in the development of crash severity indices. Work zone crash variables, variables' sub-divisions, and assigned values are listed in Tables 4.7(a), 4.7(b), and 4.7(c).

Table 4.7(a) Data Variables and Sub-Divisions

Variable	Sub-Division	Assigned Value
1- Class of Trafficway	Urban—city street	1
	Urban—other marked state highway	2
	Urban—controlled access highway	3
	Urban—toll road	4
	Urban—unmarked state highway	5
	Rural—controlled access highway	6
	Rural—other marked state highway	7
	Rural—county/local road	8
	Rural—toll road	9
2- Route Prefix	U.S. route	1
	Interstate/ Interstate business loop	2
	Illinois route/ Illinois alternate route/ Illinois business route	3
	Non-marked route	4
3- One Way Indicator	One-way	1
	Two-way	2
	One-way reversible	3
	Two-way reversible	4
4- Intersection Relevance	Yes	1
	No	2
	Not stated	0
5- Type of Construction	Construction zone	2
	Maintenance zone	3
	Utility work zone	4
	Work zone—unknown	5
6- Number of Lanes	2 lanes	2
	4 lanes	4
	6 lanes	6
	8 lanes	8
	10 lanes	10

Table 4.7(b) Data Variables and Sub-Divisions

Variable	Sub-Division	Assigned Value
7- Lane Width	10 feet	10
	11 feet	11
	12 feet	12
	> 12 feet	13
8- Road Surface Condition	Dry	1
	Wet	2
	Snow/slush	3
	Ice	4
	Sand/mud/dirt/etc.	5
9- Median Type	No median	1
	Curbed - raised median, any width	2
	Positive barrier – fencing, retaining walls, guard rails, open spaces between elevated	3
	Painted	4
	Unprotected – sodded, treated earth	5
	Rumble strips or chatter bar	6
	Mountable median	7
10- Median Width	No width	1
	01-05	2
	06-10	3
	11-30	4
	31-50	5
	51-100	6
	101-999	7
11- Traffic Control Type	No traffic control	1
	Traffic control signal	2
	Lane use control marking	3
	Stop sign or red flasher	4
	Other warning sign	5
	Police officer or flagman Railroad crossing gate	6
	Other type regulation sign	7
12- Traffic Control Functionality	No traffic control	1
	Not functioning	2
	Functioning improperly	3
	Functioning properly	4
	Reflecting material worn	5
	Missing	6

Table 4.7(c) Data Variables and Sub-Divisions

Variable	Sub-Division	Assigned Value
13- AADT	Below 10,000	1
	10,000 ~ 20,000	2
	20,000~30,000	3
	30,000 ~ 40000	4
	40,000 ~ 50,000	5
	Over than 50,000	6
14- Multiple Daily Volume	Below 2000	1
	2000 ~ 4000	2
	4000 ~ 6000	3
	6000 ~ 8000	4
	8000 ~ 10000	5
	Over than 10000	6
15- Commercial Volume	Below 2000	1
	2000 ~ 4000	2
	4000 ~ 6000	3
	6000 ~ 8000	4
	8000 ~ 10000	5
	Over than 10000	6
16- MilVehMiTrv	Below 1.736	1
	1.736~ 3.472	2
	3.472~ 5.208	3
	5.208~ 6.944	4
	6.944~ 8.68	5
	Over than 8.68	6
17- Speed Limit	30 mph	30
	35 mph	35
	40 mph	40
	45 mph	45
	50 mph	50
	55 mph	55
	60 mph	60
	65 mph	65
18- Accident Hour	6:01AM: 10:00 (Morning peak hours)	1
	10:01:16:00 (Daytime non-peak hours)	2
	16:01 : 20:00 (Afternoon peak hours)	3
	20:01 : 6:00AM (Nighttime hours)	4
19- Light Condition	Daylight	1
	Dawn	2
	Dusk	3
	Darkness	4
	Darkness—road lighted	5
20- Weather	Clear	1
	Rain	2
	Snow	3
	Fog/smoke/haze	4
	Sleet/hail	5
	Severe crosswind	6

The procedure of developing crash severity models includes two steps. First, work zone parameters that may have an impact on crash severity were identified and their sub-divisions were categorized as shown in Tables 4.7(a), 4.7(b), and 4.7(c). Second, a set of logistic regression models were developed by incorporating these work zone parameters to estimate the probability of different work zone severity indices.

Many researchers find it appealing to include many variables in their models however this may tradeoff model stability and accuracy when applied to new samples (Swalha and Sayed 2001). Some work zone variables may have negligible impact on the crash severity and therefore should be excluded not only to simplify the final model but also to increase the model accuracy. The procedure adapted in this study for variable selection is a forward procedure by which selection begins with just the intercept and then sequentially variables are added to the model one by one starting with the variable that most improves the fit (SAS 2003). The process terminates when no significant improvement can be obtained by adding any effect. The statistic used to gauge improvement in fit is an F statistic that reflects variable's contribution to the model if it is included. Therefore, at each step, the variable that yields the most significant F statistic at the 95% confidence level is added to the model while monitoring the p -values corresponding to these F statistics. The following sections present the six crash severity indices.

4.4.1 Injury Severity Index

The first crash severity index based on injury severity was developed to be a numerical value between zero and one that can be estimated form a given work zone risk factors and interpreted as the probability of a work zone to encounter severe crashes requiring hospitalization if a work zone crash occurred. The premise of this index is to build a model that describes the association between the ordinal response (injury severity) and a set of explanatory variables (such as roadway classification, median type, accident hour, light condition, AADT, and traffic control type). In this study, a logistic regression model for work zone crash severity was developed based on crash severity as a response variable of three ordered levels of severity: (1) injury other than fatal requiring hospitalization; (2) injury evident to others at scene; and (3) no visible injury. The frequency of Illinois work zone crashes in terms of injury severity is shown in Table 4.8.

Table 4.8 Frequency of Illinois Work Zone Crashes per Number of Injuries

Injury Severity	**Number of Crashes**	**Percentage**
Injury other than Fatal Requiring Hospitalization	220	14.53%
Injury Evident to Others at Scene	618	40.84%
No Visible Injury	676	44.63%
Total	1514	100%

The proportional odds model was employed to calculate the probability of severe work zone crashes to occur (injury crash requires hospitalization vs. (injury evident to others or no visible injury) given certain traffic operational, roadway geometries, and environmental conditions. The LOGISTIC procedure in SAS 9.2 was used to estimate the model parameters and assess the model goodness-of-fit (SAS 2003). As listed in Tables 4.7(a), 4.7(b), and 4.7(c), 20 explanatory variables were encompassed for estimating crash severity model parameters. All work zone variables are discrete while the response variable (crash severity) is initially considered ordinal of three levels.

Table 4.9 lists the estimated variable coefficients and related statistical results for the forward selection procedure of the cumulative logit regression model generated by

SAS when applying Fisher's scoring as an optimization technique. The analysis indicates that three work zone variables: (1) number of lanes (NL); (2) multiple daily volume; and (3) light condition have significant impact on the work zone crash severity. A correlation analysis was then conducted to identify and exclude any correlated variables among the identified independent variables in the regression model. This led to the exclusion of the second variable, which was found to be correlated with the first variable. The Wald chi-square statistic was used to test the variable significance for the logistic regression for assessing the goodness-of-fit including AIC statistic, SC statistic, and -2log likelihood statistic. AIC, Akaike Information Criterion, statistic is used to compare models accuracy since the model with the smallest AIC is considered the best. The p-value of the likelihood ratio chi-square test is 0.0001 (Chi-Square = 20.719, DF=3) which means that the global null hypothesis for the whole model is rejected. Statistically, this result indicates that the 2 predicted variables listed in the model (Table 4.9) affect work zone crash severity. Moreover, the score test for the proportional odds assumption has a p-value of 0.852 (Chi-Square is 4.26), which verifies that the model is adequately valid for fitting the data.

Table 4.9 Variables and Coefficients for the Crash Severity Index Based on Crash Severity

Section I: Variables and Coefficients				
Variable	**Estimate**	**Standard Error**	**Wald Chi-Square**	***P*-Value**
Constant	1.6587	0.1473	5.5612	0.0184
Number of Lanes (NL)	0.1420	0.0402	12.4996	0.0004
Light Condition(LC)	-0.1392	0.052	7.1696	0.0074
Section II: Testing Global Null Hypothesis: Beta=0				
Test	**Chi-Square**	**DF**	**P-Value**	
Likelihood Ratio	20.719	3	0.0001	
Score	20.224	3	0.00015	
Wald	20.986	3	0.0002	
Score Test for the Proportional Odds Assumption: Chi-Square is 4.26, Pr > ChiSq is 0.852				

The injury severity index (ISI) is presented in equation 4.7:

$$\text{ISI} = \frac{\exp[f1(x)]}{1+\exp[f1(x)]} \tag{4.7}$$

Where $f1(x) =$ -0.3475 + 0.142(NL) – 0.1392(LC)

4.4.2 Injury Severity Index-AADT Specified

Donnell and Mason (2004) claimed that annual average daily traffic (AADT) volumes can significantly affect crash severity which was also reported by many professionals (Lu et al. 2006). Although AADT was found to be one of the insignificant explanatory variables in the logistic model fitted above, it would be informative if some predictors and crash severity are investigated under conditions having precise AADT. In Illinois, it was found that more than 59% (908 crash records) of work zone injury crashes occurred in highways of AADT between 10,000 and 30,000. The frequency of Illinois work zone crashes in terms of injury severity for Highways of AADT between 10,000 and 30,000 is shown in Table 4.10.

Table 4.10 Frequency of Illinois Work Zone Crashes per Number of Injuries

Injury Severity	Number of Crashes	Percentage
Injury other than Fatal Requiring Hospitalization	128	14.1%
Injury Evident to Others at Scene	379	41.74%
No Visible Injury	401	44.16%
Total	908	100%

Based solely on 908 injury work zone crashes with AADT between 10,000 and 30,000, a new logistic regression model was performed to investigate the effect of each of the 20 independent work zone variables listed in Tables 4.7(a), 4.7(b), and 4.7(c). Table 4.11 lists the estimated variable coefficients and related statistical results for the forward selection procedure of the cumulative logit regression model generated by SAS 9.2 when applying Fisher’s scoring as an optimization technique. The review indicates that 5 work zone variables: (1) one-way indicator; (2) intersection relevance; (3) multiple daily volume; (4) light condition; and (5) surface condition have the greatest influences on the work zone crash severity. The p-value of the likelihood ratio chi-square test is 0.0001 (Chi-Square = 20.719, DF=3) which means that the global null hypothesis for the whole model is rejected. Accordingly, the inference is that the predicted five variables given in the model and shown in equation (2) influence work zone crash severity. Moreover, the score test for the proportional odds assumption has a p-value of 0.4333 (Chi-Square is 4.8588), which verifies that the model is adequately valid for fitting the data.

Table 4.11 Variables and Coefficients for the Crash Severity Index Based on Crash Severity

Section I: Variables and Coefficients				
Variable	**Estimate**	**Standard Error**	**Wald Chi-Square**	***P*-Value**
Constant	3.7611	0.7316	5.297	0.0214
One-way Indictor (OI)	-0.5845	0.3532	2.738	0.098
Intersection Relevance (IR)	-0.3380	0.17	3.954	0.0468
Surface Condition (SC)	0.0932	0.0545	2.927	0.0871
Multiple Daily Volume(MDV)	-0.2991	0.1485	4.0572	0.044
Light Condition(LC)	-0.1349	0.0671	4.404	0.0443
Section II: Testing Global Null Hypothesis: Beta=0				
Test	**Chi-Square**	**DF**	**P-Value**	
Likelihood Ratio	20.1889	5	0.0012	
Score	20.1843	5	0.0012	
Wald	19.5110	5	0.0015	
Score Test for the Proportional Odds Assumption: Chi-Square is 4.8588, Pr > ChiSq is 0.4333				

The second crash severity index based on work zone crash severity for roadways of AADT between 10,000 and 30,000 referred as, *injury severity index-AADT (ISI_AADT) specified*, is presented in equation 4.8:

$$\text{ISI\_AADT} = \frac{\exp[f2(x)]}{1+\exp[f2(x)]} \tag{4.8}$$

Where $f2(x) = 1.6839 – 0.5845(OI) – 0.338(IR) + 0.0932(SC) – 0.2991(MDV) – 0.1349(LC)$

4.4.3 Multi-Vehicles Severity Index

The third crash severity index based on number of vehicles involved in a crash was developed to be a numerical value between zero and one that can be estimated form a given work zone risk factors and interpreted as the probability of a work zone to encounter severe crashes involving multi-vehicles if a crash occurred. The premise of this index is to build a model that describes the association between the ordinal response (number of vehicles involved) and a set of explanatory variables (such as roadway classification, median type, accident hour, light condition, AADT, and traffic control type). In this study, a logistic regression model for work zone crash severity was developed based on number of vehicles involved in work zone crash as a response variable of three ordered levels: (1) single-vehicle crash; (2) two-vehicle crash; and (3) multi-vehicle crash (>2 vehicles involved). The frequency of Illinois work zone crashes in terms of number of vehicles involved per crash is shown in Table 4.12.

Table 4.12 Frequency of Illinois Work Zone Crashes per Number of Injuries

Number of Vehicles Involved	Number of Crashes	Percentage
Single-Vehicle	203	13.42%
Two-Vehicle	1036	68.44%
Multi-Vehicle	275	18.14%
Total	1514	100%

The proportional odds model was employed to calculate the probability of severe work zone crashes to occur (multi-vehicle crash vs. (single-vehicle or two-vehicle crash) given certain traffic operational, roadway geometries, and environmental conditions. The LOGISTIC procedure in SAS 9.2 was used to estimate the model parameters and assess the model goodness-of-fit (SAS 2003). As listed in Tables 4.7(a), 4.7(b), and

4.7(c), 20 explanatory variables were encompassed for estimating the second crash severity index parameters. All work zone variables are discrete while the response variable (number of vehicles involved) is initially considered ordinal of three levels.

As discussed earlier, the procedure adapted in this model for variable selection is a forward procedure by which selection begins with just the intercept and then sequentially variables are added to the model one by one starting for with the most improves the fit. Table 4.13 lists the estimated variable coefficients and related statistical results for the forward selection procedure of the cumulative logit regression model generated by SAS when applying Fisher's scoring as an optimization technique. The review indicates that 4 work zone variables: (1) trafficway class; (2) surface condition; (3) accident time; and (4) light condition have the greatest influences on the work zone crash severity. The p-value of the likelihood ratio chi-square test is <0.0001 (Chi-Square = 48.8744, DF=4) which means that the global null hypothesis for the whole model is rejected. Accordingly, the inference is that the predicted four variables given in the model and shown in equation (4.9) influence work zone crash severity.

Table 4.13 Variables and Coefficients for the Crash Severity Index Based on Number of Vehicles Involved

Section I: Variables and Coefficients				
Variable	**Estimate**	**Standard Error**	**Wald Chi-Square**	***P*-Value**
Constant	3.0371	0.1996	231.4156	<0.0001
Trafficway Class (TC)	-0.0818	0.033	6.1520	0.0131
Surface Condition (SC)	-0.0996	0.0417	5.7009	0.017
Accident Time (AT)	-0.1747	0.0585	8.9086	0.0028
Light Condition(LC)	-0.2096	0.067	9.7879	0.0018
Section II: Testing Global Null Hypothesis: Beta=0				
Test	**Chi-Square**	**DF**	**P-Value**	
Likelihood Ratio	48.8744	4	<0.0001	
Score	48.0337	4	<0.0001	
Wald	48.1672	4	<0.0001	
Score Test for the Proportional Odds Assumption: Chi-Square is 18.0197, Pr > ChiSq is 0.0012				

The multi-vehicles severity index (MVSI) is presented in equation 4.9:

$$\text{MVSI} = \frac{\exp[f3(x)]}{1+\exp[f3(x)]} \quad (4.9)$$

Where $f3(x) =$ -0.4228 – 0.0818(TC) – 0.0996(SC) – 0.1747(AT) – 0.2096(LC)

4.4.4 Multi-Vehicles Severity Index-AADT Specified

Similarly to what have been discussed in the previous crash severity index and based solely on 908 injury work zone crashes with AADT between 10,000 and 30,000 (see Table 4.14), the fourth logistic regression model was performed to investigate the effect of each of the 20 independent work zone variables listed in Tables 4.7(a), 4.7(b), and 4.7(c).

Table 4.14 Frequency of Illinois Work Zone Crashes per Number of Injuries

Injury Severity	Number of Crashes	Percentage
Single-Vehicle	112	12.33%
Two-Vehicle	634	69.82%
Multi-Vehicle	162	17.84%
Total	908	100%

Table 4.15 lists the estimated variable coefficients and related statistical results for the forward selection procedure of the cumulative logit regression model generated by SAS 9.2 when applying Fisher's scoring as an optimization technique. The review indicates that 3 work zone variables: (1) multiple daily volume; (2) speed limit; and (3) light condition have the greatest influences on the work zone crash severity. The p-value of the likelihood ratio chi-square test is <0.0001 (Chi-Square = 23.4959, DF=3) which means that the global null hypothesis for the whole model is rejected. Accordingly, the inference is that the predicted 3 variables given in the model and shown in equation (4) influence work zone crash severity.

Table 4.15 Variables and Coefficients for the Crash Severity Index Based on Number of Vehicles Involved

Section I: Variables and Coefficients				
Variable	**Estimate**	**Standard Error**	**Wald Chi-Square**	***P*-Value**
Constant (Intercept 3)	2.59	0.2848	82.7229	<0.0001
Multiple Daily Volume (MDV)	-0.6846	0.1654	17.1267	< 0.0001
Speed Limit (SL)	0.0108	0.00535	4.0623	0.0439
Light Condition(LC)	-0.1945	0.0755	6.6367	0.0100
Section II: Testing Global Null Hypothesis: Beta=0				
Test	**Chi-Square**	**DF**	**P-Value**	
Likelihood Ratio	23.4959	3	< 0.0001	
Score	22.0951	3	< 0.0001	
Wald	24.6610	3	< 0.0001	
Score Test for the Proportional Odds Assumption: Chi-Square is 6.7304, Pr > ChiSq is 0.0810				

The fourth crash severity index based on number of vehicles involved for roadways of AADT between 10,000 and 30,000 referred as, *multi-vehicles severity index-AADT (MVSI_AADT) specified*, is presented in equation 4.10:

$$\text{MVSI\_AADT} = \frac{\exp[f4(x)]}{1+\exp[f4(x)]} \qquad (4.10)$$

Where $f4(x) =$ -0.9768 – 0.6846(MDV) + 0.0108(SL) – 0.1945(LC)

4.4.5 Multi-Injuries Severity Index

Crash severity index based on number of injuries in a crash was developed to be a numerical value between zero and one that can be estimated form a given work zone risk factors and interpreted as the probability of a work zone to encounter severe crashes involving multi-injuries if a crash occurred. The premise of this index is to build a model that describes the association between the ordinal response (number of injuries) and a set of explanatory variables (such as roadway classification, median type, accident hour, light condition, AADT, and traffic control type). In this study, a logistic regression model for work zone crash severity was developed based on number of injuries involved in work zone crash as a response variable of three ordered levels:

(1) single-injury crash; (2) two-injury crash; and (3) multi-injury crash (>2 injuries). The frequency of Illinois work zone crashes in terms of number of injuries per crash is shown in Table 4.16.

Table 4.16 Frequency of Illinois Work Zone Crashes per Number of Injuries

Number of Injuries per Crash	Number of Crashes	Percentage
Single-Injury	1015	67.04%
Two-Injuries	343	22.64%
Multi-Injuries	156	10.33%
Total	1514	100%

The proportional odds model was employed to calculate the probability of severe work zone crashes to occur (multi-injuries crash vs. (single-injury or two-injury crash) given certain traffic operational, roadway geometries, and environmental conditions. The LOGISTIC procedure in SAS 9.2 was used to estimate the model parameters and assess the model goodness-of-fit (SAS 2003). As listed in Tables 4.7(a), 4.7(b), and 4.7(c), 20 explanatory variables were encompassed for estimating the second crash severity index parameters. All work zone variables are categorical while the response variable (number of injuries) is initially considered ordinal of three levels.

As discussed earlier, the procedure adapted in this model for variable selection is a forward procedure by which selection begins with just the intercept and then sequentially variables are added to the model one by one starting for with the most improves the fit. Table 4.17 lists the estimated variable coefficients and related statistical results for the forward selection procedure of the cumulative logit regression model generated by SAS when applying Fisher's scoring as an optimization technique. The review indicates that 3 work zone variables: (1) surface condition; (2) commercial volume; and (3) speed limit have the greatest influences on the work zone crash severity. The p-value of the likelihood ratio chi-square test is 0.0117 (Chi-Square =

11.0057, DF=3) which means that the global null hypothesis for the whole model is rejected. Accordingly, the inference is that the predicted three variables given in the model and shown in equation 4.11 influence work zone crash severity.

Table 4.17 Variables and Coefficients for the Crash Severity Index Based on Number of Vehicles Involved

Section I: Variables and Coefficients				
Variable	**Estimate**	**Standard Error**	**Wald Chi-Square**	***P*-Value**
Constant (Intercept 3)	-0.8693	0.1918	147.27	< 0.0001
Surface Condition (SC)	-0.0746	0.046	2.639	0.1044
Commercial Volume (CV)	-0.0765	0.0362	4.4799	0.0343
Speed Limit (SL)	0.00966	0.00401	5.798	0.0160
Section II: Testing Global Null Hypothesis: Beta=0				
Test	**Chi-Square**	**DF**	**P-Value**	
Likelihood Ratio	11.0057	3	0.0117	
Score	10.7364	3	0.0132	
Wald	10.4414	3	0.0152	
Score Test for the Proportional Odds Assumption: Chi-Square is 10.1196, Pr > ChiSq is 0.0176				

The multi-injuries severity index (MISI) is presented in equation 4.11:

$$\text{MISI} = \frac{\exp[f5(x)]}{1+\exp[f5(x)]} \tag{4.11}$$

Where $f5(x) =$ -2.3271 – 0.0746(SC) – 0.0765(CV) + 0.00966(SL)

4.4.6 Multi-Injuries Severity Index-AADT Specified

Similarly to what have been discussed in the previous crash severity index and based solely on 908 injury work zone crashes with AADT between 10,000 and 30,000 (see Table 4.18), the sixth logistic regression model was performed to investigate the effect of each of the 20 independent work zone variables listed in Tables 4.7(a), 4.7(b), and 4.7(c).

Table 4.18 Frequency of Illinois Work Zone Crashes per Number of Injuries

Number of Injuries	**Number of Crashes**	**Percentage**
Single-Injury	598	65.86%
Two-Injuries	204	22.47%
Multi-Injuries	106	11.67%
Total	908	100%

Table 4.19 lists the estimated variable coefficients and related statistical results for the forward selection procedure of the cumulative logit regression model generated by SAS when applying Fisher's scoring as an optimization technique. The review indicates that 3 work zone variables: (1) route prefix; (2) surface condition; and (3) speed limit have the greatest influences on the work zone crash severity. The p-value of the likelihood ratio chi-square test is 0.0227 (Chi-Square = 9.5618, DF=3) which means that the global null hypothesis for the whole model is rejected. Statistically, the inference is that the predicted 3 variables given in the model and shown in equation (6) influence work zone crash severity. Moreover, the score test for the proportional odds assumption has a p-value of 0.9814 (Chi-Square is 0.1758), which verifies that the model is adequately valid for fitting the data.

Table 4.19 Variables and Coefficients for the Crash Severity Index Based on Crash Severity

Section I: Variables and Coefficients				
Variable	**Estimate**	**Standard Error**	**Wald Chi-Square**	***P*-Value**
Constant	-1.2140	0.3077	15.5668	< 0.0001
Route Prefix (RP)	0.1019	0.0664	2.3535	0.125
Surface Condition (SC)	-0.1057	0.0657	2.5913	0.1074
Speed Limit (SL)	0.0107	0.00525	4.1226	0.0423
Section II: Testing Global Null Hypothesis: Beta=0				
Test	**Chi-Square**	**DF**	**P-Value**	
Likelihood Ratio	9.5618	3	0.0227	
Score	9.0522	3	0.0286	
Wald	8.9025	3	0.0306	
Score Test for the Proportional Odds Assumption: Chi-Square is 0.1758, Pr > ChiSq is 0.9814				

The sixth crash severity index based on number of injuries per work zone crashes for roadways of AADT between 10,000 and 30,000 referred as, *multi-injuries severity index-AADT (MISI_AADT) specified*, is presented in equation 4.12:

$$\text{MISI\_AADT} = \frac{\exp[f6(x)]}{1+\exp[f6(x)]} \quad (4.12)$$

Where $f6(x) =$ -2.5899 – 0.1019(RP) – 0.01057(SC) + 0.0107 (SL)

4.4.7 Validation of Crash Severity Indices

The developed crash severity indices were validated using a sample of 200 crash cases selected randomly from HSIS Illinois work zone crash data for a 5 year period between 2003 and 2008. As discussed earlier, the crash severity indices were developed to represent the probability of a work zone to encounter: (1) severe injury crashes; (2) multi-vehicles crashes; and (3) multi-injuries crashes. The actual crash dataset, however, include the real data of: (a) injury severity; (b) number of vehicles involved; and (c) number of injuries. In these models, a work zone crash is considered severe if: (i) the crash had an serious injury that require hospitalization; or (ii) the crash involved more than 2 vehicles; or (iii) the crash had more than 2 injuries. Otherwise, the work zone crash is considered non-severe. In order to validate the new models, crash severity indices were calculated for each crash record using equations 4.7, 4.8, 4.9, 4.10, 4.11, and 4.12. A criterion of 0.5 was set for all indices (i.e. if the crash severity index ≥ 0.5, this indicates a severe crash, and if the crash severity index < 0.5, this indicates a non-severe crash). Table 4.20(a) and 4.20(b) present a sample of the predicted severity calculated using the crash severity indices versus the actual severity of crashes calculated for the first and second indices. The percentage of error in predicting the right severity condition (severe vs. non-severe) was calculated for the six crash severity indices and the results are summarized in Table 4.21.

Table 4.20(a) Predicted Injury Severity Using Injury Severity Index (ISI)

Crash Case	Crash Severity		Work Zone Parameters Used in Calculating ISI			Predicted Injury Severity Indix	
	Injury Severity	Severity	Number of Lanes	Multiple Daily Volume	Light Condition	ISI (Eq. 4.7)	Predicted Severity
1	2.00	Non-Severe	4.00	1.00	1.00	0.49	Non-Severe
2	2.00	Non-Severe	4.00	1.00	1.00	0.49	Non-Severe
3	3.00	Non-Severe	4.00	1.00	1.00	0.49	Non-Severe
4	2.00	Non-Severe	4.00	2.00	1.00	0.45	Non-Severe
5	2.00	Non-Severe	6.00	1.00	1.00	0.56	Severe
6	3.00	Non-Severe	4.00	1.00	1.00	0.49	Non-Severe
7	1.00	Severe	10.00	2.00	5.00	0.53	Severe
8	3.00	Non-Severe	4.00	1.00	1.00	0.49	Non-Severe
9	2.00	Non-Severe	4.00	1.00	1.00	0.49	Non-Severe
10	2.00	Non-Severe	4.00	1.00	1.00	0.49	Non-Severe
11	2.00	Non-Severe	2.00	1.00	1.00	0.42	Non-Severe
12	3.00	Non-Severe	4.00	1.00	9.00	0.24	Non-Severe
13	3.00	Non-Severe	4.00	1.00	5.00	0.35	Non-Severe
14	2.00	Non-Severe	4.00	1.00	1.00	0.49	Non-Severe
15	2.00	Non-Severe	4.00	1.00	1.00	0.49	Non-Severe
16	3.00	Non-Severe	4.00	1.00	5.00	0.35	Non-Severe

Table 4.20(b) Predicted Injury Severity Using Injury Severity Index-AADT (ISI_AADT)

Crash Case	Crash Severity		Work Zone Parameters Used in Calculating ISI_AADT					Predicted Injury Severity Index	
	Injury Severity	Severity	Oneway Indicator	IntersectionRel	Surface Condition	Multiple Daily Volume	Light	ISI_AADT (Eq. 4.8)	Predicted Severity
1	2.00	Non-Severe	2	1	1	1	1	0.46	Non-Severe
2	2.00	Non-Severe	2	1	1	1	1	0.46	Non-Severe
3	3.00	Non-Severe	2	1	2	1	1	0.48	Non-Severe
4	2.00	Non-Severe	2	1	1	2	1	0.39	Non-Severe
5	2.00	Non-Severe	2	2	1	1	1	0.38	Non-Severe
6	3.00	Non-Severe	2	1	1	1	1	0.46	Non-Severe
7	1.00	Severe	2	1	9	1	1	0.64	Severe
8	3.00	Non-Severe	2	2	1	1	1	0.38	Non-Severe
9	2.00	Non-Severe	2	1	1	1	1	0.46	Non-Severe
10	2.00	Non-Severe	2	1	1	1	1	0.46	Non-Severe
11	2.00	Non-Severe	2	1	1	1	1	0.46	Non-Severe
12	3.00	Non-Severe	2	1	1	1	9	0.22	Non-Severe
13	3.00	Non-Severe	2	1	1	1	5	0.33	Non-Severe
14	2.00	Non-Severe	2	1	1	1	1	0.46	Non-Severe
15	2.00	Non-Severe	2	1	2	1	1	0.48	Non-Severe
16	3.00	Non-Severe	2	1	1	1	5	0.33	Non-Severe

Table 4.21 Accuracy of Crash Severity Indices

Crash Severity Index	Percentage of Error
1- Injury Severity Index (ISI)	19%
2- Injury Severity Index-AADT Specified (ISI_AADT)	18%
3- Multi-Vehicles Severity Index (MVSI)	19%
4- Multi-Vehicles Severity Index AADT Specified (MVSI_AADT)	19%
5- Multi-Injuries Severity Index (MISI)	13%
6- Multi-Injuries Severity Index AADT Specified (MISI_AADT)	13%

4.5 RECOMMENDATIONS BASED ON WORK ZONE CRASH ANALYSIS

This section presents a set of recommendations for improving work zone practices based on the comprehensive data analysis of work zone crashes in Illinois. The recommendations to improve work zone layouts based on this data analysis are grouped in the following five categories: (1) work zone layout; (2) work zone strategies; (3) work zone standards; (4) temporary traffic control; and (5) other recommendations.

4.5.1 Work Zone Layout

This section presents the main findings and recommendations to improve work zone layouts in order to increase safety and minimize work zone crashes.

1- The analysis of work zone crashes revealed that the majority of injury work zone crashes occurred at intersections. This important finding highlights the need to revise the design and implementation of existing work zone layouts and temporary traffic control plans at entrance and exit ramps on interstates.

2- The potential crash causes of “road engineering”, “markings”, “vision obscured” and “improper lane usage” were found in the data analysis to contribute to more than 30% of single vehicle injury crashes and almost 20% of fatal and multi-vehicle crashes. Accordingly, work zone layouts and delineation need to be carefully designed according to standard specifications and inspected to ensure that traffic control plans are safe and effective for both the travelling public and construction workers.

3- Construction work zones had the highest percentage of crashes compared to maintenance and utility work zones. Construction zones accounted for 88% of fatal crashes, 90% of injury crashes involving one or more vehicles, and 88% of injury crashes involving only one vehicle. Accordingly, special attention should be given to the layouts of construction zones and all their related safety measures.

4- The results of the crash analysis indicated that 44% and 40.5% of fatal crashes and injury crashes involving only one-vehicle, respectively, occurred at nighttime hours (08:00PM ~ 6:00AM). This indicates that nighttime work zones create safety risks for traffic causing a significant percentage of the total number of fatal crashes and injury crashes involving one vehicle only. These increased nighttime risks need to be carefully considered and addressed in the layout and lighting design arrangements of nighttime work zones to improve their visibility, reduced their nighttime lighting glare and increase the alertness of nighttime drivers.

5- Four lane highways have high percentages of work zone crashes. This finding calls for special traffic management plans on this type of roadways.

6- Medians were found to be an important factor that affects the number of work zone crashes. Almost 40% of work zone crashes occurred in roadways with no medians compared to only 15% of crashes occurred in roadways with positive barrier medians. This highlights the safety benefits and need for utilizing positive barrier medians such as movable concrete barriers, fencing, guard rail, and retaining wall in construction zones whenever possible.

4.5.2 Work Zone Strategy

This section presents recommendations to improve work zone strategies based on the main findings of the conducted data analysis of work zone crashes in Illinois.

1- Intersections were found to be one of the major contributing factors of work zone crashes since the majority of injury crashes (77%) occurred at intersections. Accordingly, various work zone strategies such as road closures and detours especially at interstate entrance ramps of short durations should be considered and used whenever possible to minimize this risk.

2- Work zone crashes at higher speed limits were more frequent and severe when compared to those at lower speed limits. The percentage of fatal crashes significantly dropped for construction zones with speed limits of 40 mph and lower. In order to minimize the risk of work zone crashes, speed limits need to be reduced and enforced in open traffic lanes near the work area.

3- A significant percentage of fatality and injury work zone crashes occurred during darkness, dawn and dusk. Accordingly, work during these nighttime periods need to be carefully planned to minimize the hazards of nighttime construction.

4- Illinois routes experienced high percentage of crash frequencies at a 45 mph speed limit while interstate routes experienced high percentage of crash frequencies at 55 mph speed limit. Accordingly, work zone speed limits need to be reduced at both Illinois and interstate routes.

4.5.3 Work Zone Standards

This section focuses on recommendations to improve work zone standards based on the findings of work zone crash data analysis.

1- Special attention should be given to work zones on "interstates in national highway systems" since it had the highest percentage of fatal and injury work zone crashes.

2- Standards of work zones can be modified to require contractors to use positive barrier medians since it has a significant impact on reducing the frequency and severity of work zone crashes.

3- Almost 30% of injury work zone crashes occurred at AADT between 10,000 and 20,000. Beyond that peak range, the rate of work zone crashes tends to gradually decrease in roads with higher ranges of AADT. The majority of work zone crashes whether fatal or injury occurred in roads with commercial volume below 2000 and the rate of work zone crashes tends to gradually decrease as the commercial volume of the road increases. These findings recommend that current standards should be altered to reflect the potential hazard of work zones in roadways of AADT between 10,000 and 20,000 and having commercial volume below 2000.

4- The majority of fatal crashes (62%) occurred at higher speed limits (55 mph or more) compared to only 25% of injury crashes that occurred at these same speed limits. The percentage of fatal crashes also significantly dropped to less than 8% for construction zones that had a speed limit of 40 mph or lower. This indicates that higher speed limits increase the severity of work zone crashes. Accordingly, speed limits need to be reduced and enforced to minimize the frequency and severity of work zone crashes.

4.5.4 Work Zone Temporary Traffic Control

This section presents a set of recommendations to improve the utilization of Temporary Traffic Control (TTC) measures in work zones in order to improve safety.

1- The effectiveness of current TTC measures needs improvement in order to minimize the frequency and severity of work zone crashes. The data analysis showed that 54% of speed-related work zone crashes occurred on roads that had regular traffic control signals and 69% of work zone crashes were caused by improper driving. This indicates that current TTC practices need improvements to maximize compliance with speed limits and to alert inattentive drivers. Accordingly, the utilization of police patrols and automated photo enforcement of speeding violations need to be increased. In addition, innovative TTC countermeasures such as temporary rumble strips, speed displays, message boards should also be adopted to increase drivers' alertness.

2- The analysis of work zone crashes reveals that approximately 40% of fatal and injury related work zone crashes occurred in work zones that had no traffic signals or rigorous restrictions at the scene of the crash. This highlights the need to increase the utilization of advanced warning signals such as message boards, digital speed displays, flashing arrow boards, and temporary rumble strips.

3- A significant percentage of work zone crashes (44% of fatal crashes and 47% of injury crashes) occurred in work zones that have either no traffic control devices or malfunctioning ones. This highlights the need to improve the current practices for inspecting and enforcing the functionality of traffic control devices in work zones.

4- Only 5% of the fatal crashes and 3% of the injury crashes occurred in the presence of a police officer or flagger. This confirms the significant impact of police enforcement and flaggers in reducing work zone crashes.
5- The results of the analysis show that the most frequent type of collision was rear-end for both fatal crashes (22%) and all injury crashes (43%). Moreover, the analysis shows that 40% of rear-end crashes occurred in Illinois routes. This highlights the need for TTC devices that can be used to alert drivers approaching work zones of the potential slow down and traffic backup.
6- The correlation analysis of crash contributing causes and collision type revealed that almost half of rear-end crashes were due to speed. This highlights the need to utilize more effective TTC ahead of work zones to reduce speed such as temporary rumble strips and speed displays.
7- The crash analysis results showed that 21% of fatal crashes occurred in darkness without road lighting compared to 9% of total injury crashes that occurred in similar lighting conditions. This suggests that nighttime work zones on dark roads are more likely to cause fatal crashes than injury crashes. Accordingly, the lighting conditions in nighttime work zones need to be carefully designed and implemented to improve visibility and traffic safety.

4.5.5 Other Recommendations

This section presents a set of general recommendations to improve work zone practices.

1- The analysis of work zone crashes shows that improper driving represents the highest contributing cause for both fatal and injury work zone crashes, followed by speed and work zone environment causes. Improper driving covers a number of driver actions such as following too closely, wrong side/way, improper turn, and right turn on red. Speed contributing causes represent a number of observations such as “exceeded authorized speed limits”, “exceeded safe speed for conditions”, and “failure to reduce speed to avoid crash”. These findings highlight the need for improving public awareness of work zone hazards and the consequences of exceeding speed limit.

2- Drivers’ distraction was the contributing cause of almost 10% of fatal work zone crashes which highlights the need to control and minimize potential causes of drivers’ distraction such as the use of cell phones or texting while driving.

3- As with any typical study based on traffic crash databases, the findings of data analysis have limitations due to that lack of information regarding various work zone layout parameters such as work zone duration, layout, and strategy. Accordingly, future reporting and data collection of work zone crashes need to be expanded to report work zone parameters that can be used in the future to support the identification and documentation of potential contributing causes of work zone crashes.

CHAPTER 5

IMPACT OF LAYOUT PARAMETERS ON THE RISK OF CRASH OCCURRENCE

5.1 INTRODUCTION

The FHWA Work Zone Safety and Mobility Rule highlights the importance of analyzing work zone crash data and the role it can play in improving work zone layouts (FHWA 2005). This FHWA rule also reports that field diaries of construction operations often log incidents and actions such as the need to replace channelization devices into their proper positions after knockdown by an errant vehicle, which provide indications of safety or operational deficiencies. These deficiencies should be appropriately addressed while the knowledge gained should be spread to other zones to control any potential hazards of work zones in future projects. To gather and analyze this valuable field information on work zone layouts and their impact on safety, two research tasks are conducted: (1) site visits of highway work zones; and (2) an online survey of Illinois resident engineers. This chapter presents: (1) the results of site visits; (2) a detailed analysis of the survey results; (3) a new metric for calculating the monetary value of work zone crashes; and (4) IDOT resident engineers' recommendations to improve work zone current and future practices.

5.2 SITE VISITS

In order to identify practical factors that affect the safety of highway construction zones, three highway construction sites were visited and studied in Illinois over October 2009. During these site visits, data were gathered on (1) the type of construction operations that were performed during daytime hours; (2) the layout of work zone designed for these operations; and (3) the type of traffic control countermeasures being in use. The locations of these site visits are: Bloomington, IL (I-74); Bloomington, IL (I-55); and Downs, IL (I-74). The following sections present a brief description of the gathered data during each of these three site visits.

5.2.1 Bloomington, IL (I-74)

This project which is located on I-74 Bloomington, IL was visited on October 1st, 2009. The observed construction operations on that highway construction project were, paving, compacting, and milling operations. The main types of traffic devices that were utilized on site included: (1) direction indicator barricades; (2) vertical barricades; (3) drums; (4) arrow boards; (5) work limiting signs; and (6) a flagger to alert and slow traffic. These traffic control devices and the running construction operation are shown in Figures 5.1, 5.2, and 5.3. The traffic management plan (TMP) of this construction operation follows Illinois Department of Transportation (IDOT) standard 701406-05, Lane Closure, Freeway/Expressway, Day Operations Only. This standard was used whenever construction operations would encroach on the lane adjacent to the shoulder. Work zone speed limit signs and Flagger signs should be moved as necessary to maintain 200-foot spacing between the signs and the workers in each separate work activity (IDOT Standard 701406-05). The layout of this standard is shown in Figure 5.4. Other Temporary Traffic Control (TTC) signs followed the MUTCD typical application 33 as shown in Figure 3.3 (MUTCD 2003). The distances A, B, and C for this typical application are calculated using Table 2.4 while the taper length L is calculated using Table 2.1 and Table 2.2 (MUTCD 2003).

Figure 5.1 Direction indicator barricades, drums, and arrow boards

Figure 5.2 Flagger with a slow sign

Figure 5.3 Vertical barricades at a resurfacing operation

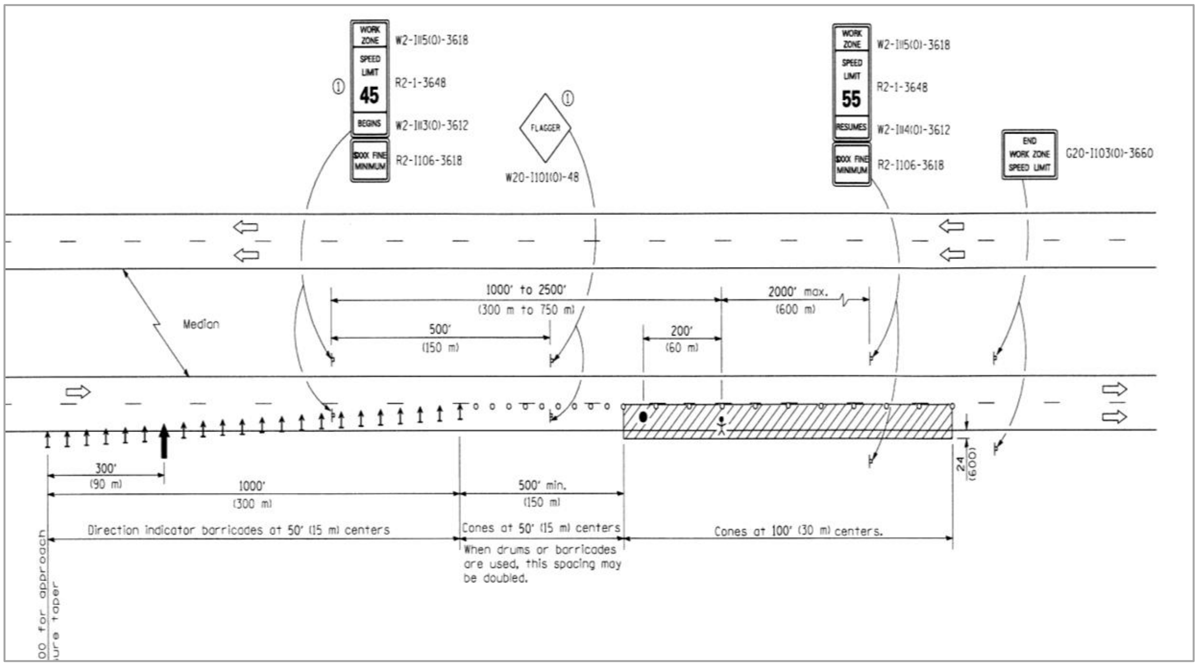


Figure 5.4 IDOT Standard 701406-05 Lane Closure Day Operations Only

5.2.2 Bloomington, IL (I-55)

This project which is located on I-55 Bloomington, IL was visited on October 2nd, 2009. The construction operation on that project was bridge rehabilitation at the entrance of the ramp. On the day of visit, there were no running operations however, one lane was still closed and the other one was reduced. This work zone had experienced a large number of work zone crashes (> 20 crashes in 15 days) till the authority decided to close the ramp for public. The main types of traffic devices that were utilized on site included: (1) direction indicator barricades; (2) vertical barricades; (3) drums; (4) arrow boards; (5) work limiting signs; and (6) temporary concrete barriers. These traffic control devices and the running construction operation are shown in Figures 5.5, 5.6, and 5.7. Before the decision of closing the ramp for public, the TMP of this construction operation followed IDOT Standard 701411-05, Application 2, Lane Closure, Multilane at Entrance Ramp for Speeds ≥ 45 mph. The layout of this standard is shown in Figure 5.8. The resident engineer stated that the high number of crashes of this work zone was because of the existence of intense trees at the entrance of the intersection which obstructed the clear vision of the upstream traffic especially at night. Reduced traffic lanes were considered at this work zone besides the use of outer shoulder.

Figure 5.5 Ramp closed on I-55

Figure 5.6 Potential damage in temporary concrete barriers

Figure 5.7 Vision obstruction of trees at the entrance of the work zone

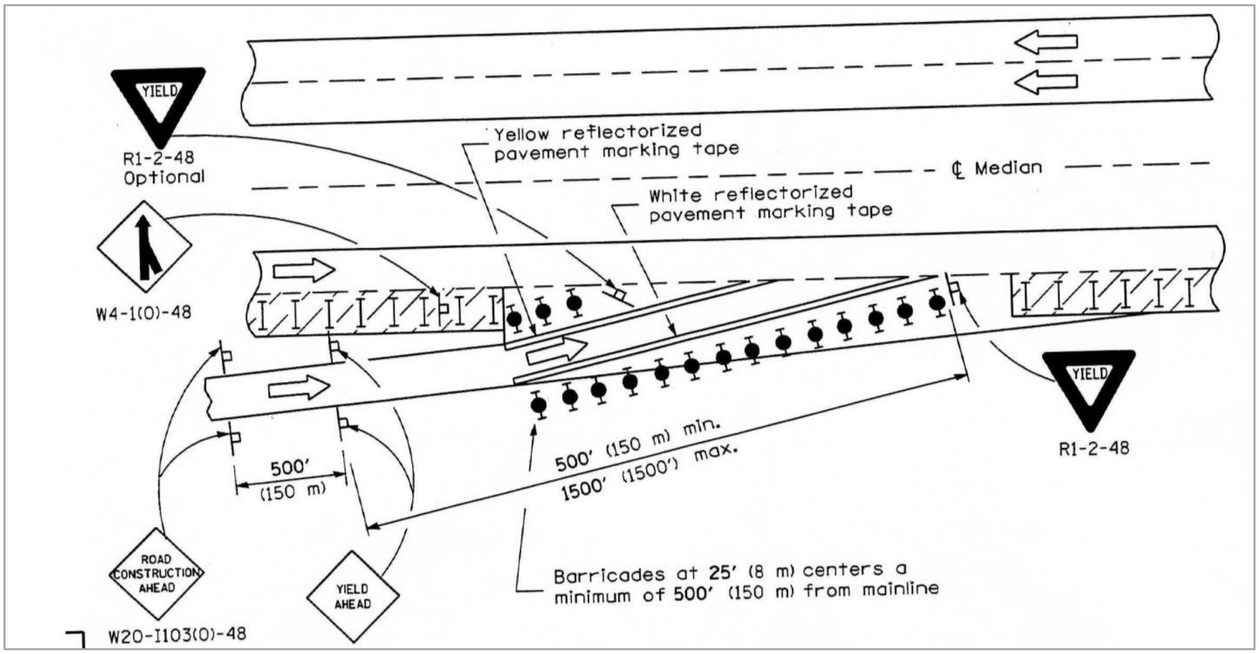


Figure 5.8 IDOT Standard 701411-05, Application 2, Lane Closure, Multilane at Entrance Ramp for Speeds ≥ 45 mph

5.2.3 Downs, IL (I-74)

This highway construction project which is located on I-74 Downs, IL was visited on October 5nd, 2009. The observed construction operations were bridge rehabilitations. The main types of traffic devices that were utilized on site included: (1) direction indicator barricades; (2) vertical barricades; (3) drums; (4) arrow boards; (5) work limiting signs; and (6) temporary concrete barriers. These traffic control devices and the running construction operation are shown in Figures 5.9, 5.10, and 5.11. The TMP of this construction operation follows IDOT standard 701422-02, Lane Closure, Multilane, for Speeds ≥ 45 mph to 55 mph. Reduced traffic lanes were considered at this TMP. This standard was used whenever construction operations would encroach on the lane adjacent to the shoulder. The layout of this standard is shown in Figure 5.12.

Figure 5.9 Bridge rehabilitation on Downs, IL (I-74)

Figure 5.10 Temporary concrete barriers, drums, and barricades

Figure 5.11 Reduced traffic lane at the termination

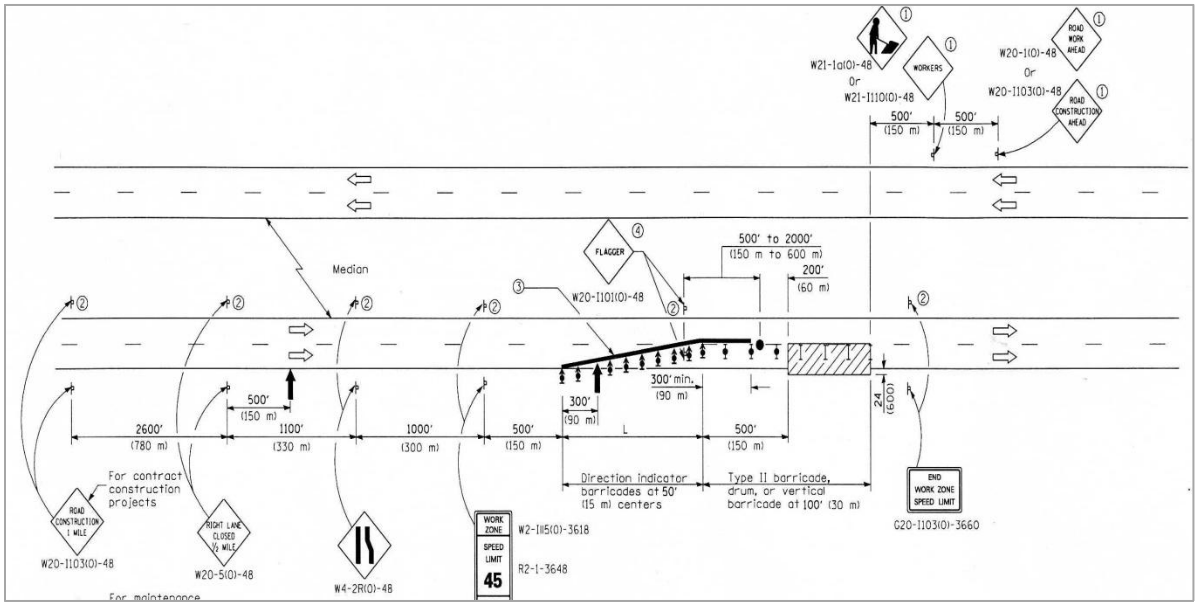


Figure 5.12 IDOT Standard 701422-02, Lane Closure, Multilane, for Speeds ≥ 45 mph to 55 mph

5.3 SURVEY DESIGN

The survey on work zone practices sponsored by the Illinois Department of Transportation (IDOT) was designed to gather information on the impact of 64 work zone parameters that are grouped in 11 divisions on the risk of crash occurrence. The survey was distributed to Illinois resident engineers who were asked to identify the risk level of work zone parameters, identify the importance of these parameters according to its impact on work zones safety, and provide recommendations and suggestions to improve work zone layouts and efficient placement of temporary rumble strips within and prior to work zones.

The survey development follows the guidelines of the American Association for Public Opinion Research (AAPOR 2010). The number of resident engineers in IDOT was estimated to be around 250 resident engineers representing all IDOT districts. The online survey was sent to all district resident engineers and complete responses were received from 146 resident engineers, with a response rate of 58%. At a variability level of 0.5, and confidence level of 90%, this response rate (146/250) has a permissible error of ±4% (Williams and Protheroe 2008). In other words, if a survey result shows that 94% of resident engineers rank "multilane closure at entrance ramp" as high risk, we can be 90% confident that the percentage of the whole population of IDOT resident engineers who believed the high risk of "multilane closure at entrance ramp" would fall somewhere in the range between 90% and 98%. The following sections present in details the survey design followed by a discussion of the impact of work zone parameters on the risk of crash occurrence and IDOT resident engineers' recommendations to improve work zone practices.

The survey consisted of three main sections, as shown in Appendix B. The first section required Illinois resident engineers to identify the impact of 64 work zone parameters on the risk level of crash occurrence in and around the highway work area. The 64 parameters were categorized in 11 divisions: (1) work zone layout; (2) work zone hours; (3) work zone duration; (4) usage of right-side or median shoulder as a temporary traffic lane; (5) work zone type; (6) roadway classification; (7) reduced lane width; (8) median type; (9) traffic control devices; (10) vision obstructions; and (11) work zone speed limit. A comprehensive list of work zone parameters associated with each of these 11 divisions was developed by the research team and was then reviewed and revised by the Technical Review Panel (TRP) of this project to identify typical work zone layout parameters that may have an impact on crash occurrences. In the first section of the survey, IDOT resident engineers were asked to evaluate and identify the risk level of crash occurrence associated with each work zone parameter on a scale ranging from "1" to "5", where "1" indicates "lowest risk" and "5" indicates "highest risk". The work zone categories and their parameters are presented in more detail in the following sections.

The second section of the survey required IDOT resident engineers to evaluate the importance of the 11 work zone divisions according to their impact on the safety of work zones. A scale ranging from "1" to "5" has been used, where "1" indicates "least importance" and "5" indicates "highest importance". The influence of work zone parameters on the safety of work zones will be used together with risk levels of work zone parameters to identify the impact of work zone parameters on the safety of work zones.

The third section of the survey included three questions asking resident engineers for their feedback and recommendations on:

1- Improving work zone layouts to minimize crashes in and around the work area;

2- Types and efficiency of innovative work zone or traffic control devices; and

3- Possible locations to place temporary rumble strips within work zone layouts.

The following sections present a detailed analysis of IDOT resident engineers' responses for each of the 11 work zone divisions followed by a discussion of the impact of work zone parameters on the risk level of crash occurrence. A detailed analysis of resident engineers' suggestions and recommendations for improving work zone layout and placing temporary rumble strips will be presented in sections 5.7, 5.8, 5.9, and 5.10.

5.4 IMPACT OF WORK ZONE PARAMETERS ON THE RISK OF CRASH OCCURRENCE

This section presents the impact of the analyzed 11 work zone divisions and their 64 parameters on the risk level of crash occurrence. The analysis was based on the complete responses of 146 IDOT resident engineers. The number of resident engineers corresponding to each work zone parameter at the 5 risk levels was first counted and then analysis of outliers was performed. Chauvenet's criterion was used in this study to identify outliers which can occur by chance in any data distribution for the following two reasons: (1) they are genuinely different from the rest of the data, or (2) errors took place during the collection and recording process (Sawalha and Sayed 2001). Table 5.1 presents the average risk level of work zone parameters on crash occurrence (values are modified to be between "0" and "1" where "0" represents no risk while "1" represents the highest risk). The following sections discuss in more detail the risk level associated with each of the 11 work zone categories.

Table 5.1 Work Zone Parameters Average Risk Levels

	Work Zone Parameters	Parameter Number	Average	Variance
1- Work Zone Layout	Use of Shoulder	1	0.38	0.06
	Median Crossover	2	0.42	0.05
	Divergence	3	0.47	0.05
	One Lane Closure on Freeway/Expressway	4	0.51	0.06
	Two Lane Closure on Freeway/Expressway	5	0.63	0.05
	Multilane Closure at Exit Ramp	6	0.67	0.06
	Multilane Closure at Entrance Ramp	7	0.71	0.04
2- Work Zone Speed Limit	35 mph	1	0.24	0.06
	45 mph	2	0.43	0.04
	55 mph	3	0.67	0.06
	Advisory Speed Reduction Only	4	0.72	0.04
	No Work Zone Speed Reduction	5	0.89	0.04
3- Work Zone Vision Obstructions	Glare from Sun	1	0.75	0.04
	Horizontal or Vertical Curves	2	0.66	0.05
	Glare from Headlights	3	0.63	0.06
	Construction Equipment	4	0.61	0.05
	Glare from Nighttime Work Zones	5	0.59	0.06
	Signs	6	0.46	0.06
	Trees	7	0.42	0.08
	Temporary Concrete Barriers	8	0.40	0.05
4- Traffic Lane Width	All Lanes Open for Traffic (Off-Road Operations)	1	0.16	0.04
	One or More Lanes Closed (Traffic Lane Width = 12	2	0.46	0.03
	One or More Lanes Closed (Traffic Lane Width < 12	3	0.67	0.04
	Pavement Edge Drop-off	4	0.72	0.05
5- Work Zone Hours	Daytime (10:01AM - 4:00PM)	1	0.46	0.04
	Night (8:01PM - 6:00AM)	2	0.67	0.11
	Afternoon (4:01PM - 8:00PM)	3	0.75	0.04
	Morning (6:01AM - 10:00AM)	4	0.76	0.04
6- Work Zone Duration	Long Term Stationary Operations (D > 3 days)	1	0.39	0.05
	Intermediate Term Stationary Operations (1 day > D	2	0.56	0.04
	Short Term Stationary Operations (D > 30 minutes)	3	0.67	0.04
	Mobile Operations (D < 15 minutes)	4	0.68	0.05
7- Usage of Right-side or Median Shoulders	Full Shoulders and Lane Constricted	1	0.45	0.05
	Lane Constricted by Temporary Concrete Barriers	2	0.46	0.05
	Shoulder Pavement Structure is Different	3	0.55	0.05
	Narrow Shoulders and Lane Constricted	4	0.70	0.04
	High Traffic Volume	5	0.75	0.05
8- Median Type	Positive Barrier - Fencing - Retaining Walls - Guard F	1	0.29	0.07
	Rumble Strip or Chatter Bar	2	0.36	0.04
	Curbed - Raised Median - Any Width	3	0.37	0.04
	Mountable Median	4	0.41	0.04
	Unprotected - Sodded - Treated Earth	5	0.46	0.04
	Painted	6	0.50	0.04
	Bi-directional Turn Lanes	7	0.55	0.04
	No Median	8	0.66	0.05
9- Roadway Type	Two Lanes	1	0.52	0.04
	Controlled Access Highways	2	0.53	0.07
	Multilane Rural without Access Control	3	0.58	0.05
	Urban and Suburban Arterials	4	0.64	0.05
10- Work Zone Type	Shoulder Closure Only Operations	1	0.34	0.05
	Bridge - Culvert Construction and Maintenance	2	0.43	0.04
	Delivery Truck Entrance - Exit	3	0.58	0.05
	HMA Paving	4	0.59	0.05
	Pavement Striking and Marking	5	0.59	0.06
	Pavement Sawing - Patching	6	0.66	0.05
	Work Zone Setup - Access	7	0.68	0.05
11-Type of TTC Devices	Arrow Boards	1	0.70	0.04
	Automated Photo Enforcement	2	0.72	0.05
	Channelization Devices	3	0.71	0.04
	Flagger	4	0.69	0.05
	Message Boards	5	0.71	0.06
	Police Presence	6	0.95	0.02
	Speed Displays	7	0.66	0.05
	Truck Mounted Attenuators (TMAs)	8	0.66	0.05

5.4.1 Work Zone Layout

Seven work zone layouts were selected to represent typical layouts of work zones. Table 5.1 shows that the work zone layout of “multilane closure at entrance ramp” has the highest average risk level of 0.71 followed by “multilane closure at exit ramp” that had a risk level of 0.67 while the layouts of “median crossover” and “use of shoulder” have the lowest average risk levels of 0.42 and 0.38 respectively. As shown in Figure 5.13(a), a significant majority of IDOT resident engineers (approximately 75%) reported that the three work zone layouts of “median crossover”, “divergence”, and “use of shoulder” create low to medium risk levels of crash occurrence (≤ 0.5), while more than 94% of resident engineers reported that the layout of “multilane closure at entrance ramp” causes a high risk of crash occurrence (≥0.5).

5.4.2 Work Zone Speed Limit

Work zone speed limit was found to be statistically correlated with the frequency of work zone crashes (El-Rayes et al. 2009). Accordingly, this survey was designed to study the impact of five types of speed limits on the risk of crash occurrence: (1) 35 mph; (2) 45 mph; (3) 55 mph; (4) advisory speed reduction only; and (5) no work zone speed reduction. IDOT resident engineers were asked to identify the impact of each speed limit parameter on the risk level of crash occurrence. Work zones of “no speed reductions” were reported by resident engineers to create the highest average risk level of 0.89 (see Table 5.1). On the other hand, work zones of “speed limit 35 mph” were reported to create the least average risk level of 0.24. Figure 5.13(b) shows that almost 70% of resident engineers identified work zones with “only advisory speed reduction” to have high risk levels (≥0.75). Moreover, the survey results show that increasing speed limit leads to a steady increase in the level of crash occurrence risks (Figure 5.13(b)).

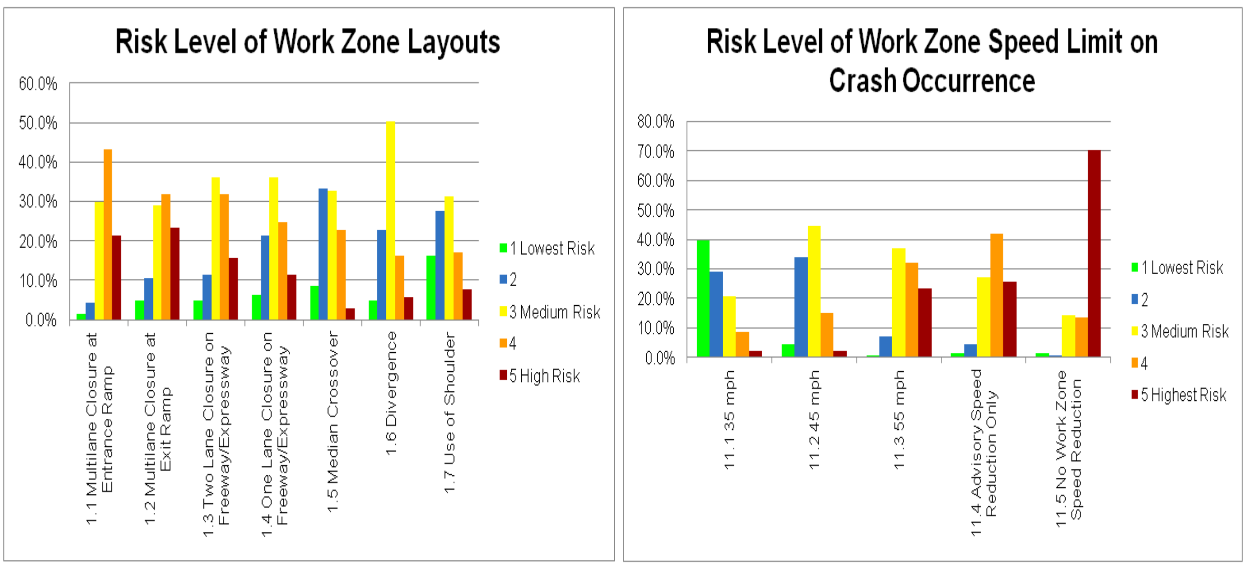
5.4.3 Vision Obstructions

During a construction site visit, one of the interviewed resident engineers reported that many of the work zone crashes that he witnessed occurred at intersections that had vegetation obstacles blocking drivers' vision. Accordingly, this section of the survey was designed to study the impact of vision obstructions on the risk level of crash occurrence. This category of vision obstructions includes eight main types: (1) trees; (2) signs; (3) construction equipment; (4) glare from sun; (5) glare from headlights; (6) glare from nighttime work zones; (7) horizontal or vertical curves; and (8) temporary concrete barriers. Illinois resident engineers were asked to identify the impact of each vision obstruction on the risk level of crash occurrence. Vision obstruction that is caused by "glare from the sun" was identified by resident engineers to create the highest average risk level (0.75) of crash occurrence. On the other hand, the majority of resident engineers (83.7%) reported that "temporary concrete barriers" created low to medium risk level (≤ 0.5) of crash occurrence. As shown in Figure 5.13(c), more than 85% of survey respondents indicated that vision obstruction caused by "construction equipment", "horizontal and vertical curves", "glare from headlights" and "glare from nighttime work zones" caused high risk (≥0.6).

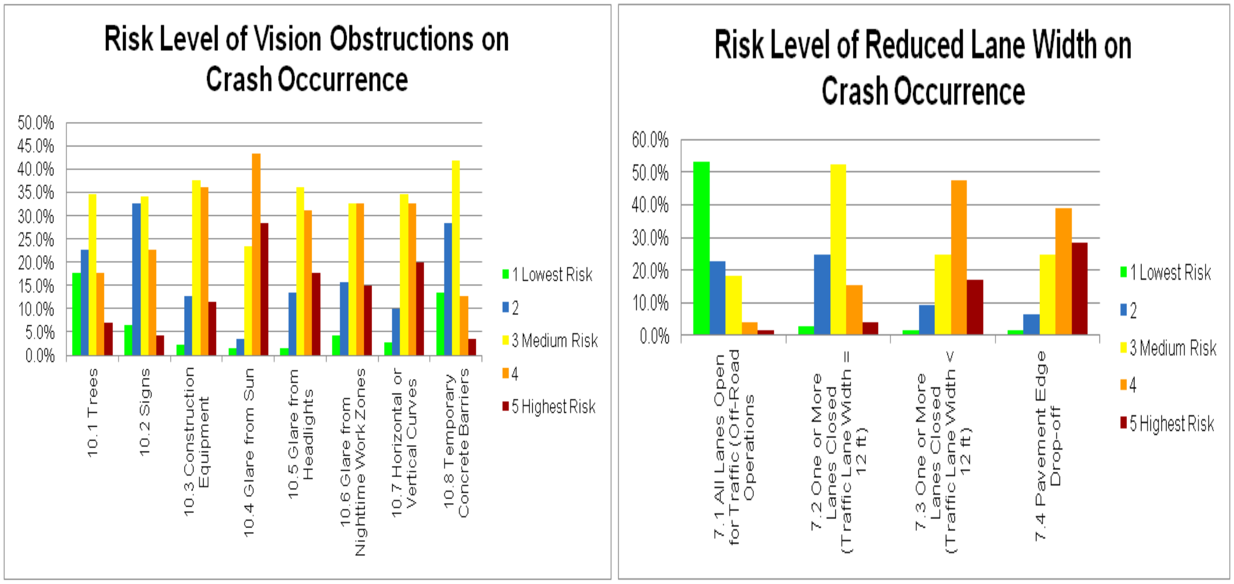
5.4.4 Reduced Lane Width

The layout of many highway construction work zones often requires partial lane closures or a reduction in the width of open traffic lanes. The impact of this reduction in lane width on the risk of work zone crashes is analyzed in this section of the survey.

This category includes four types of lane closures and/or lane width reduction: (1) all lanes open for traffic (off-road operations); (2) one or more lanes closed (traffic lane width = 12 ft); (3) one or more lanes closed (traffic lane width < 12 ft); and (4) pavement edge drop-off. IDOT resident engineers were asked to indicate the impact of each of these four parameters on the risk of work zone crashes. Table 5.1 shows that work zones that allow "all lanes to be open for public traffic" had the least risk of crash occurrence (0.16). On the other hand, work zones of "pavement edge drop-off" had the highest risk of crash occurrence (0.72). The majority of resident engineers (90%) indicated that work zones that had "one or more lanes closed (traffic lane width < 12 ft)" create medium to high risk levels (≥ 0.6) of crash occurrence, as shown in 5.13(d).



(a) **Figure 5.13** **(b)**



(c) **(d)**

Figure 5.13 Risk levels of work zone parameters on crash occurrence: (a) work zone layouts; (b) work zone speed limit; (c) vision obstructions; and (d) traffic lane width

5.4.5 Work Zone Hours

Work zones were categorized in this section based on their operation hours into four daily periods: (1) morning that extends from 6:01AM to 10:00AM; (2) daytime that covers 10:01AM to 4:00PM; (3) afternoon that extends from 4:01PM to 8:00PM; and (4) night that covers 8:01PM to 6:00AM, as shown in Table 5.1. IDOT resident engineers were then asked to identify the risk level associated with each of the four periods on crash occurrence. The daytime period (10:01AM to 4:00PM) was reported by a significant percentage of IDOT respondents to create the least risk of crash occurrence 0.46. Other periods of the day were reported to have average risk levels that ranged between 0.67 and 0.76. On the other hand, a significant percentage of resident engineers (39%) identified “nighttime period that extends from 8:01PM to 6:00AM” to have the highest risk (level 5) as shown in Figure 5.14(a).

5.4.6 Work Zone Duration

Based on IDOT operation standards, work zones have been categorized in this section into four main categories based on their duration length D: (1) long term stationary operations (D ≥ 3 days); (2) intermediate term stationary operations (1 day > D > 3 days); (3) short term stationary operations (D > 30 minutes); (4) mobile operations (D < 15 minutes). Table 1 shows that the majority of resident engineers (80.2%) indicated that “long term stationary operations (D ≥ 3 days)” would have low to medium risk levels (≤ 0.3) on crash occurrence. On the other hand, the majority of resident engineers (86%) identified “short term stationary operations (D > 30 minutes)” to have medium to high risk levels (≥ 0.6) on crash occurrence. The two work zone durations that had the highest average risk levels were (1) “short term stationary operations (D > 30 minutes)” that had an average risk level of 0.67; and (2) “mobile operations (D < 15 minutes)” that had an average risk levels of 0.68. More than half of the resident engineers identified “intermediate term stationary operations (1 day > D > 3 days)” to have medium risk (see Figure 5.14 (b)).

5.4.7 Use of Right-side or Median Shoulder as a Temporary Traffic Lane

This category analyses the impact of utilizing the right-side or median shoulder as a temporary traffic lane on work zone safety. Accordingly, this category includes five parameters: (1) narrow shoulders and constricted lanes; (2) full shoulders of lane constricted; (3) shoulder pavement structure is different; (4) high traffic volume; and (5) lanes constricted by temporary concrete barriers. IDOT resident engineers were asked to report their perception of risk associated with each of these parameters. As shown in Table 1, work zones with “shoulders subjected to high traffic volume” and “narrow shoulders of lane constrictions" were reported to have the highest average of risk level of 0.75 and 0.7, respectively. Furthermore, Figure 5.14(c) shows that a significant percentage of resident engineers (~40%) indicated that "shoulder pavement structure" and "lane constriction by temporary concrete barrier" represent medium risk level on crash occurrence.

5.4.8 Median Type

Median types were found to be statistically correlated with the frequency of work zone crashes in the second interim report of this project (El-Rayes et al. 2009). Accordingly, this survey was designed to collect IDOT resident engineers' perceptions on the impact of different types of work zone medians on the risk level of crash occurrence. This category of median types included 8 parameters of work zone medians that match the types identified by IDOT and listed in the guidebook for the Illinois state data files released by the Highway Safety Information System (Council and Mohamedshah 2009). The eight median types are: (1) no median; (2) unprotected – sodded, treated earth; (3) curbed raised median, any width; (4) positive barrier; (5) rumble strips or chatter bar; (6) painted; (7) bi-directional turn lanes; and (8) mountable medians. Illinois resident engineers were asked to identify the risk level of each of these eight median types. Work zones that had "no median" were reported by IDOT resident engineers to have the highest average risk level of 0.66. On the other hand, work zones that had "positive barriers, fencing, retaining walls, and guard rails" were reported to have the least risk level of 0.29 (see Table 5.1). A significant percentage of resident engineers identified work zones that had "rumble strips medians" to have a low risk level of 0.36, as shown in Figure 5.14(d).

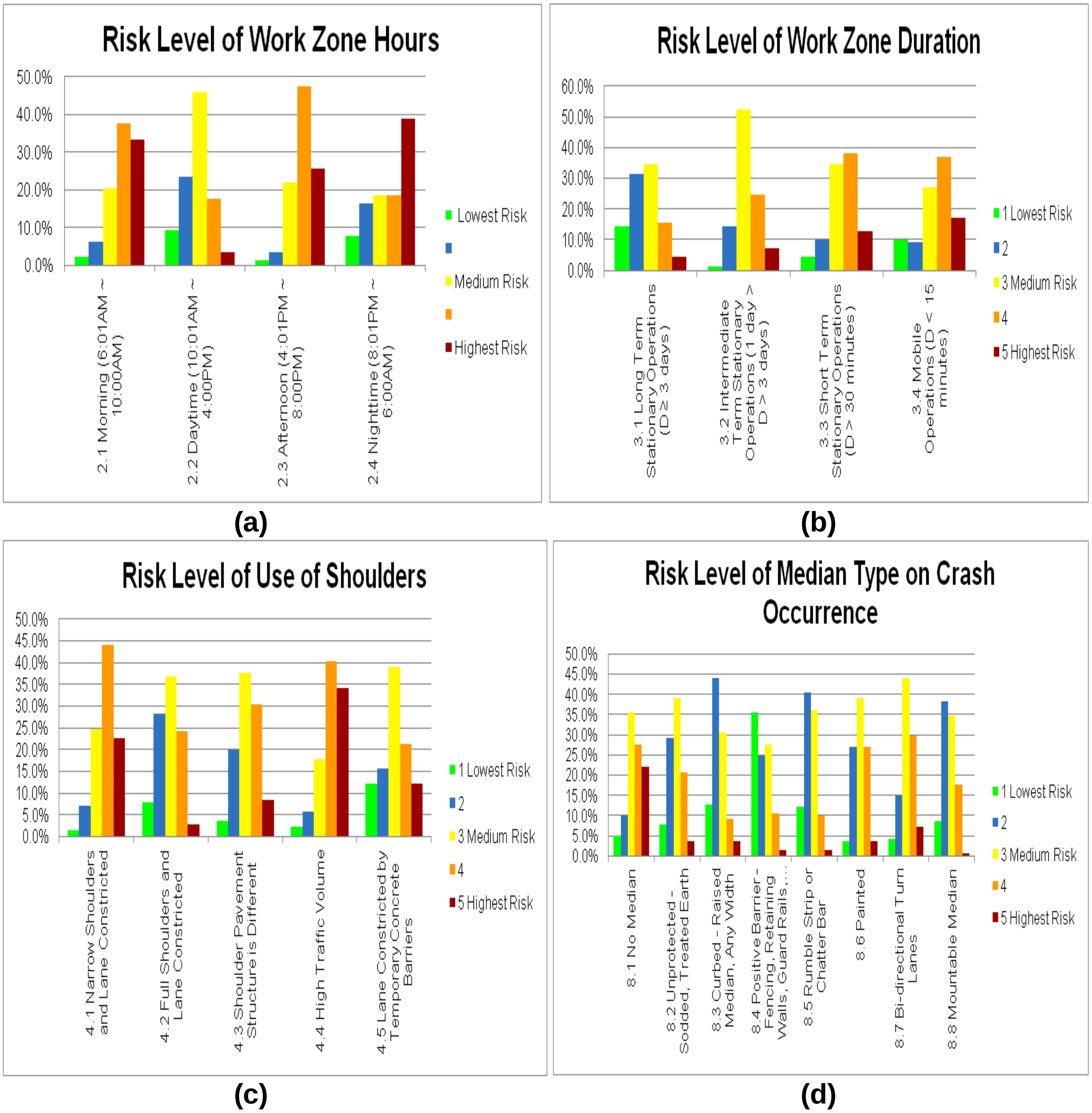


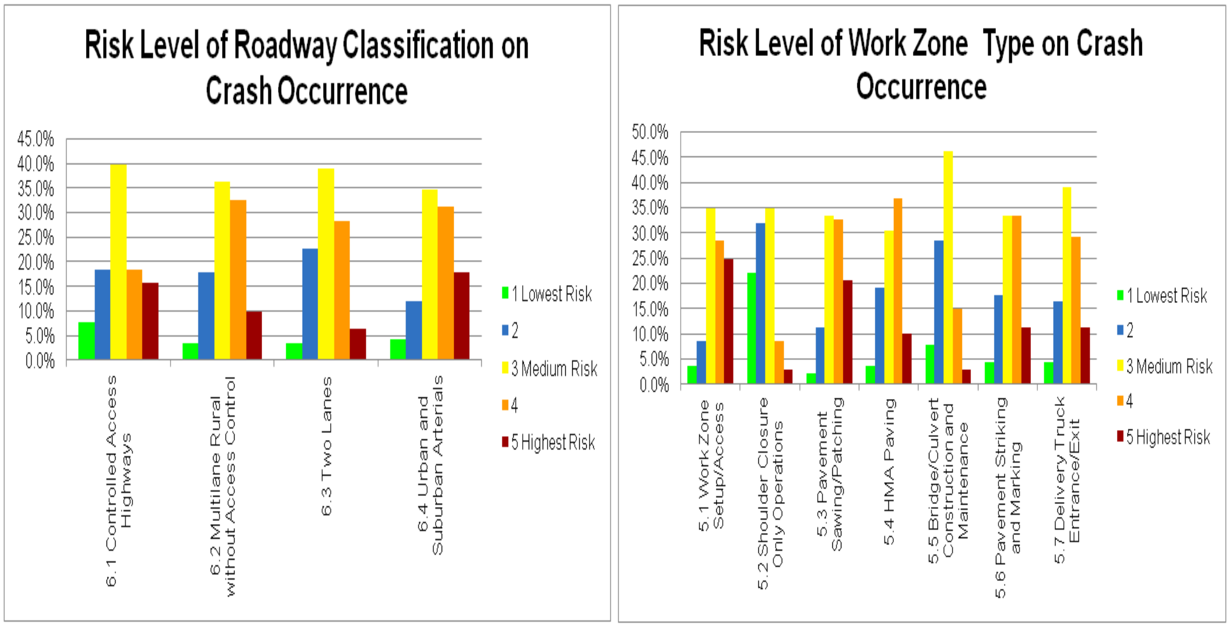
Figure 5.14 Risk levels of work zone parameters on crash occurrence: (a) work zone hours; (b) work zone duration; (c) use of shoulders; and (d) median type

5.4.9 Roadway Type

In order to avoid any confusion that may result from the various classifications of roadway types, the authors in this study utilized the roadway classification of the Manual on Uniform Traffic Control Devices (MUTCD). Therefore, the roadway category in the survey includes four roadway types: (1) controlled access highways; (2) multilane rural without access control; (3) two lanes; and (4) urban and suburban arterials. IDOT resident engineers were then asked to identify the risk level of work zones of these four roadway types on crash occurrence. The results of the survey indicate that IDOT resident engineers did not report a significant difference of risk among the four types of roadways (see Table 5.1). Figure 5.15(a) shows that a significant percentage of resident engineers identified a medium risk level of 0.56 for the analyzed four types of roadways.

5.4.10 Work Zone Type

The type work zone in this survey was classified into seven main types: (1) work zone setup/access; (2) shoulder closure only operations; (3) pavement sawing/patching; (4) HMA Paving; (5) bridge/culvert construction and maintenance; (6) pavement striking and marking; and (7) delivery truck entrance/exit. IDOT resident engineers were then asked to identify the risk level associated with each of the 7 work zone types. Table 5.1 shows that “work zone setup/access” and “pavement sawing/patching” were identified by IDOT resident engineers to have the highest average risk level of 0.67. On the other hand, work zone types of “shoulder closures only operations” and “maintenance operations” had the minimum average risk level of 0.34 and 0.43 respectively. A significant percentage of resident engineers (46%) have reported that “bridge/culvert construction and maintenance” to cause a medium risk of 0.43 as shown in Figure 5.15 (b).



(a) **(b)**

Figure 5.15 Risk levels of work zone parameters on crash occurrence: (a) roadway type; (b) work zone type

5.4.11 Effectiveness of Temporary Traffic Controls

The type of Temporary Traffic Control (TTC) countermeasures applied within work zones was found to be statistically correlated with the frequency of work zone crashes (El-Rayes et al. 2009). The survey on work zone practices was designed to analyze the effectiveness of eight TTC countermeasures that are typically used in most IDOT operations. IDOT resident engineers were asked to identify the effectiveness of each device/countermeasure in preventing crashes on a scale ranging from “0” to “1”, where “0” indicates “lowest effectiveness” and “1” indicates “highest effectiveness”. A consensus on the effectiveness of “police enforcement” on reducing work zone crash occurrence can be identified from the results shown in Figure 5.16 since resident engineers reported its average effectiveness as 0.95. Other TTC countermeasures had average effectiveness that ranged between 0.66 and 0.72.

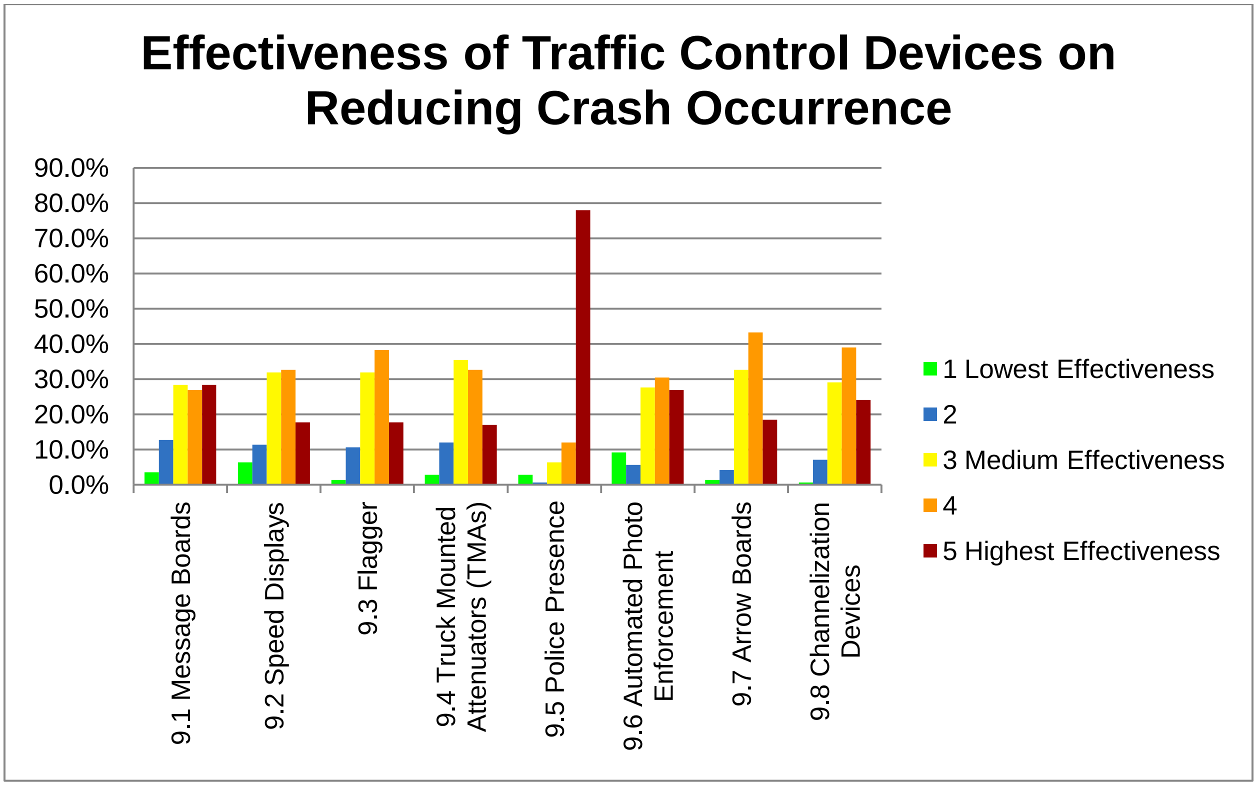


Figure 5.16 Effectiveness of temporary traffic control countermeasures on reducing crashes

The results of the survey indicate that IDOT resident engineers did not report a significant difference of risk among different types of roadways as shown in Table 5.1. Therefore, roadway parameters will be omitted and 57 work zone parameters will be considered for quantifying the risk level and probability of crash occurrence associated with work zones. Work zone parameters have been divided into two groups: (1) hazard work zone parameters that increase the probability of crash occurrence (βWZ); and (2) temporary traffic control parameters that mitigate the probability of crash occurrence (βTTC).

Group (1) represents work zone hazard parameters that are organized in nine categories that include 49 parameters, as shown in Table 5.2. The average risk level for each of these parameters was calculated based on IDOT resident engineer responses. The risk impact factor, calculated as (1 + average risk level), represents the impact of each parameter in increasing the risk of crash occurrence. Risk impact factors of each category were then normalized by dividing the value of the risk impact factor by the minimum value of risk impact factor in this category. New normalized risk impact factors are represented in Table 5.2 as ($\beta WZ \geq 1$). The effectiveness of 8 temporary traffic control (TTC) measures represented as group (2) was calculated based on IDOT resident engineer responses (see Table 5.3). The probability of crash occurrence was calculated as (1-Effectiveness). Normalized values were calculated and represented in Table 5.3 as ($\beta TTC \leq 1$) to represent the probability of work zone crash occurrence based on the effectiveness of TTC countermeasures. The methodology adapted for calculating βTTC has followed the same procedure of calculating crash modification factors (CMF) suggested by FHWA (http://safety.fhwa.dot.gov/tools/crf/).

Table 5.2 Risk Levels of Work Zone Parameters and Associated Probability of Crash Occurrence (βWZ)

	Work Zone Parameters	Parameter Number	Average Risk Level	Risk Impact Factor	β(Work Zone)	
1- Work Zone Layout	Median Crossover	1	0.42	1.42	1.00	β (Layout)
	Divergence	2	0.47	1.47	1.04	
	One Lane Closure on Freeway/Expressway	3	0.51	1.51	1.06	
	Two Lane Closure on Freeway/Expressway	4	0.63	1.63	1.14	
	Multilane Closure at Exit Ramp	5	0.67	1.67	1.17	
	Multilane Closure at Entrance Ramp	6	0.71	1.71	1.20	
2- Work Zone Speed Limit	35 mph	1	0.24	1.24	1.00	β (Speed)
	45 mph	2	0.43	1.43	1.16	
	55 mph	3	0.67	1.67	1.35	
	Advisory Speed Reduction Only	4	0.72	1.72	1.39	
	No Work Zone Speed Reduction	5	0.89	1.89	1.53	
3- Work Zone Vision Obstructions	Glare from Sun	1	0.75	1.75	1.25	β (Vision)
	Horizontal or Vertical Curves	2	0.66	1.66	1.18	
	Glare from Headlights	3	0.63	1.63	1.16	
	Construction Equipment	4	0.61	1.61	1.15	
	Glare from Nighttime Work Zones	5	0.59	1.59	1.13	
	Signs	6	0.46	1.46	1.04	
	Trees	7	0.42	1.42	1.02	
	Temporary Concrete Barriers	8	0.40	1.40	1.00	
4- Traffic Lane Width	One or More Lanes Closed (Traffic Lane Width = 12 ft)	1	0.46	1.46	1.00	β (Lane)
	One or More Lanes Closed (Traffic Lane Width < 12 ft)	2	0.67	1.67	1.14	
	Pavement Edge Drop-off	3	0.72	1.72	1.18	
5- Work Zone Hours	Daytime (10:01AM - 4:00PM)	1	0.46	1.46	1.00	β (time)
	Night (8:01PM - 6:00AM)	2	0.67	1.67	1.15	
	Afternoon (4:01PM - 8:00PM)	3	0.75	1.75	1.20	
	Morning (6:01AM - 10:00AM)	4	0.76	1.76	1.21	
6- Work Zone Duration	Long Term Stationary Operations (D > 3 days)	1	0.39	1.39	1.00	β (Duration)
	Intermediate Term Stationary Operations (1 > D > 3 days)	2	0.56	1.56	1.13	
	Short Term Stationary Operations (D > 30 minutes)	3	0.67	1.67	1.20	
	Mobile Operations (D < 15 minutes)	4	0.68	1.68	1.21	
7- Use of Shoulders	Full Shoulders and Lane Constricted	1	0.45	1.45	1.00	β (Shoulder)
	Shoulder Pavement Structure is Different	2	0.55	1.55	1.07	
	Narrow Shoulders	3	0.70	1.70	1.17	
	Shoulders Subjected to High Traffic Volume	4	0.75	1.75	1.21	
8- Median Type	Positive Barrier - Fencing - Retaining Walls Elevated	1	0.29	1.29	1.00	β (barrier)
	Rumble Strip or Chatter Bar	2	0.36	1.36	1.06	
	Curbed - Raised Median - Any Width	3	0.37	1.37	1.06	
	Mountable Median	4	0.41	1.41	1.09	
	Unprotected - Sodded - Treated Earth	5	0.46	1.46	1.13	
	Painted	6	0.50	1.50	1.16	
	Bi-directional Turn Lanes	7	0.55	1.55	1.20	
	No Median	8	0.66	1.66	1.29	
9- Work Zone Type	Maintenance Operations	1	0.34	1.34	1.00	β (Type)
	Bridge - Culvert Construction and Maintenance	2	0.43	1.43	1.07	
	Delivery Truck Entrance - Exit	3	0.58	1.58	1.17	
	HMA Paving	4	0.59	1.59	1.18	
	Pavement Striking and Marking	5	0.59	1.59	1.19	
	Pavement Sawing - Patching	6	0.66	1.66	1.24	
	Work Zone Setup - Access	7	0.68	1.68	1.25	

Table 5.3 Effectiveness of TTC Countermeasures and Associated Probability of Crash Occurrence (βTTC)

	Work Zone Parameters	Parameter Number	Effectiveness	1 - Effectiveness	β(TTC)
11-Type of TTC Devices	Arrow Boards	1	0.70	0.30	0.86
	Automated Photo Enforcement	2	0.72	0.28	0.83
	Channelization Devices	3	0.71	0.29	0.84
	Flagger	4	0.69	0.31	0.90
	Message Boards	5	0.71	0.29	0.84
	Police Presence	6	0.95	0.05	0.16
	Speed Displays	7	0.66	0.34	0.98
	Truck Mounted Attenuators (TMAs)	8	0.66	0.34	1.00

5.5 MONETARY VALUE OF WORK ZONE CRASHES

The monetary value of crash costs are used in economic analyses to evaluate proposed safety regulations and to choose among alternative improvements to existing highway systems. In 1992, the FHWA published a technical report that presented comprehensive costs that individuals are willing to pay to reduce the number and severity of crashes. The most recent Costs published by the National Work Zone Safety Information Clearinghouse shows that injury costs fluctuate between $6,000 for minor injury crash and $3,000,000 for a fatality crash. Practical and accurate estimate of work zone crashes is of great importance to be used in benefit-cost analyses.

This section presents a new metric for calculating work zone crash costs based on: (1) βTTC: the effectiveness of temporary traffic control countermeasures in work zones; (2) βWZ: the probability of crash occurrence due to various work zone parameters; (3) n_a: number of crashes per work zone mile; (4) v_a: average cost of work zone crash; (5) L: work zone length; and (6) $nZones$: number of work zone setups during construction. Work zone crash cost per zone is formulated in Eq. 5.1.

$$C_c = \beta\mathrm{TTC} \text{ x } \beta\mathrm{WZ} \text{ x } n_a \text{ x } v_a \text{x L x } (1.05)^{nZones} \quad (5.1)$$

Where, βTTC is the first modification factor that takes into account the effectiveness of the temporary traffic control countermeasure applied at the construction site and its effect on reducing the probability of crash occurrence. Values of βTTC are presented in Table 5.3. βWZ is the second modification factor that characterizes the impact of 9 work zone parameters on increasing the probability of work zone crash occurrence. βWZ is calculated as shown in Eq. 5.2. The probability of crash occurrence associated with each parameter is presented in Table 5.2.

$$\beta\mathrm{WZ} = \beta(\mathrm{Layout}) \text{ x } \beta(\mathrm{Speed}) \text{ x } \beta(\mathrm{Vision}) \text{ x } \beta(\mathrm{Lane}) \text{ x } \beta(\mathrm{Hours}) \text{ x } \beta(\mathrm{Duration}) \text{ x } \beta(\mathrm{Shoulder}) \text{ x } \beta(\mathrm{Median}) \text{ x } \beta(\mathrm{Type}) \quad (5.2)$$

The number of crashes per mile work zone, n_a, is calculated using Eq. 5.3 based on Illinois recent crash data. Annual data of improved/constructed highways and bridges for the most recent three years (2006, 2007, and 2008) were collected and used in this study as summarized in Table 5.4 (IDOT 2006a, IDOT 2007a, and IDOT 2008a). Each improved/constructed bridge was assumed to represent 3 miles of construction. The total number of work zone crashes for the three years were collected and presented in Table 5.4. Eq. 5.3 was used to calculate the average number of crashes per work zone mile for the three years and n_a average is taken as 5 crashes per work zone mile.

$$n_a = \frac{Total\ number\ of\ work\ zone\ crashes\ per\ year}{Average\ workzone\ miles\ constructed\ per\ year} \quad (5.3)$$

Table 5.4 Number of Crashes per Work Zone Mile; 2006, 2007, and 2008 (IDOT 2006, 2007, 2008)

	2008	2007	2006
Total miles of highways (improved or constructed)	897	597	734
Total number of bridges (improved or constructed)	278	255	270
Average constructed/improved work zone miles	1731	1362	1544
Total number of work zone crashes per year	7813	7729	8326
n_a**: number of crashes per work zone mile**	4.5	5.67	5.39
n_a ***"Average"*** **=** $\sum \frac{4.5+5.67+5.39}{3} = 5\ crashes\ per\ mile$ **work zone**			

The most recent injury costs classified by injury severity and published by the National Work Zone Safety Information Clearinghouse (NWZSIC) are presented in Table 5.5. The severity of Illinois work zone crashes is represented in three levels: (1) fatal crashes; (2) injury crashes; and (3) property damage crashes (PDO). The cost of fatality per work zone crash was assumed to be $3,000,000 based on comprehensive costs published by NWZSIC. The cost of injury was calculated based on the composition of injury crashes in Illinois work zones analyzed in Chapter 3 and 4. An average value for the cost of injury crash is estimated to be $111,000 (see Table 5.6). The cost of PDO crash was assumed 6,000 per crash (see Table 5.5). The average cost per work zone crash, v_a, was first calculated for each year by dividing the total cost of work zone crashes by the total number of crashes. Then the average cost of work zone crash for the three years was calculated to be $44,131.

Table 5.5 Comprehensive Costs by Injury Scale (National Work Zone Safety Information Clearinghouse 2002)

Injury Severity	Cost per Injury
Minor	6,000
Moderate	45,000
Serious	175,000
Severe	565,000
Critical	2,290,000
Fatal	3,000,000

Table 5.6 Composition of Illinois Work Zone Crashes

Serious Injury needs Hospitalization	Moderate Injury Evident to others at Crash Scene	Minimum/No Visible Injury
16%	40%	44 %
565,000	45,000	6,000
Injury Work Zone Cost = $\sum \frac{565{,}000 \times 16 + 45{,}000 \times 40 + 6{,}000 \times 44}{100} = \$\mathbf{111{,}040}\ \boldsymbol{per\ crash}$		

Table 5.7 Average Cost of work zone crash; 2006, 2007, and 2008 (IDOT 2006b, 2007b, 2008b)

	2008	2007	2006
Total number of work zone crashes per year	7813	7729	8326
Number of fatal crashes	31	18	23
Number of fatalities	31	21	29
Cost of Fatal Crashes(Assuming $3,000,000 per fatility)	93000000	63000000	87000000
Number of injury crashes	1386	1431	1586
Number of injuries	1985	2007	2268
cost of Injury Crashes (Assuming $111,000/injury)	220335000	222777000	251748000
Number of property damage crashes (PDO)	6396	6280	6717
Cost of PDO crashes (Assuming $6,000 per crash)	38376000	37680000	40302000
Total cost of work zone crashes	351711000	323457000	379050000
Va: Average cost of work zone crash	45,016	41,850	45,526
v_a ***"Average"*** = $\sum \frac{45{,}016+41{,}850+45{,}526}{3} = \$\mathbf{44{,}131}\ \boldsymbol{per\ work\ zone\ crash}$			

The project length, L, represents the total project length whether the project is short term (Duration < 1 day) or long term (Duration > 1day). IDOT resident engineers reported that work zone setup represents one of the significant hazards for both travelling public and construction workers. In order to account for the risk level of crash occurrence associated with the number of work zone setups, the crash cost metric in Eq. 5.1 is modeled as a function of the number of setups, $nZones$, as an exponent to a base of 1.05 that represents the normalization of paving operations with respect to work zone setup/access (see Table 5.1). The presented new metric for calculating the monetary value of work zone crashes will be integrated in a model that optimize work zone setup parameters to minimize total work zone costs including: (1) construction cost; (2) user delay cost; and (3) crash cost as discussed in Chapter 6.

5.6 RECOMMENDATIONS OF IDOT RESIDENT ENGINEERS TO IMPROVE WORK ZONE PRACTICES

This section presents the recommendations of IDOT resident engineers to improve work zone layout in order to minimize work zone crashes based on their answers to the first question of the survey as previously presented in section 5.2. Responses to this question in the survey have been received from 85 IDOT resident engineers out of the total 146 complete survey responses, with a response rate of 60%. Recommendations to improve work zone layout have been grouped in 5 categories: (1) work zone layout; (2) work zone strategies; (3) work zone standards; (4) temporary traffic control; and (5) other recommendations. The categorized responses are presented in details in the following sections and the exact responses are presented in Appendix C.

5.6.1 Work Zone Layout

This section presents IDOT resident engineers’ recommendations to improve work zone layout as shown in Table 5.8. Each recommendation and the corresponding number of IDOT engineers who recommended it are presented in Table 5.8.

Table 5.8 IDOT Resident Engineers Recommendations to Improve Work Zone Layout

Recommendations to Improve Work Zone Layout	Number of IDOT Engineers Providing Recommendations
1. Work zone Layout should be done according to the specifications, inspected by traffic control engineer with a thorough check of consultants' plans to make sure that their traffic control plans match the specifications. The delineations should be checked before and through work zones.	4
2. The taper length should be increased, inspected, maintained, and be represented through solid row of channel devices while arrow boards should be placed in the appropriate locations relative to the tapers.	3
3. Traffic control set up should be performed two weeks before starting the job using Truck Mounted Attenuators (TMA) and signs of upcoming work.	3
4. Work zone layout could be done on Sundays while less traffic exists on day time.	1
5. Lane closures near or after a crest in a hill or in a horizontal curve should be avoided whenever possible.	1
6. Vegetation at early warning/work zone signage should be trimmed to allow better sight distance at intersections.	1
7. Traffic barriers should be used on roadways with 4 or more lanes.	1
8. A consistency should be followed from site to site based on road use (interstate, urban highway, rural highway, etc).	1
9. Many of the current layouts should be simplified for the motoring public.	1
10. The plans should accurately present the layout and match field conditions rather than blind application of standards.	1

5.6.2 Work Zone Strategy

This section presents IDOT resident engineers' recommendations to improve work zone strategies, as shown in Table 5.9. Each recommendation and the corresponding number of IDOT engineers who recommended it are presented in Table 5.9.

Table 5.9 IDOT Resident Engineers Recommendations to Improve Work Zone Strategies

Recommendations to Improve Work Zone Strategies	Number of IDOT Engineers Providing Recommendations
1. More road closures and detours especially at interstate entrance ramps of short durations should be considered because this will save lots of money and improve the quality of the finished product by not having to cut the work up in pieces for staging, and put the traffic on a safe and unobstructed route to travel.	6
2. Speed limits should be reduced.	6
3. Stage construction creates many conflicts. Therefore, more crossovers should be adopted using concrete barriers providing 2 lanes through work zones.	3
4. An additional advanced warning sign (Stopped Traffic Ahead) with flashers would alert motorists.	1
5. Work after dark should be minimized.	1
6. Traffic detours during 3R projects of 6 months of construction time should be utilized.	1

5.6.3 Work Zone Standards

This section presents IDOT resident engineers' recommendations to improve work zone standards, as shown in Table 5.10. Each recommendation and the corresponding number of IDOT engineers who supports it are presented in Table 5.10.

Table 5.10 IDOT Resident Engineers Recommendations to Improve Work Zone Standards

Recommendations to Improve Work Zone Standards	**Number of IDOT Engineers Providing Recommendations**
1. Many of the current standards are quiet generic that it should be altered to match IDOT, tailored to each situation, or considered as guidelines with permitted flexibility for professional engineers to make engineering decisions to address actual field conditions especially at side roads and off-ramps.	5
2. Standards are not descriptive enough for stage construction plans.	1
3. Work zone standards should be adjusted for the roadway geometry (horizontal and vertical curves) and the terrain (trees or tall grass).	1
4. Standards need to be simplified. Too much information is confusing and distracting.	1
5. Standards of mobile operations on highways with speed limits of more than 55mph or high ADTs should be eliminated.	1
6. Enforced 45 mph speed limits on all roadways marked 55 and over.	1

5.6.4 Work Zone Temporary Traffic Control

This section presents IDOT resident engineers' recommendations to improve work zone temporary traffic control devices, as shown in Table 5.11. Each recommendation and the corresponding number of IDOT engineers who recommended it are presented in Table 5.11.

Table 5.11 IDOT Resident Engineers Recommendations to Improve Work Zone Temporary Traffic Control Devices

Recommendations to Improve Work Zone Temporary Traffic Control (TTC) Devices	Number of IDOT Engineers Providing Recommendations
1. More police presence would greatly reduce the frequency of work zone crashes on both the interstate and the secondary rural highways as well. It is crucial to have it when setting traffic control devices or laying out work zones.	12
2. The usage of as much advanced warning as possible is highly recommended. This includes larger and more visible signs, message boards, speed display boards, arrow boards, rumble strips, speed limit enforcement, and speed bumps.	11
3. Flaggers are effective while more protection should be considered for them through utilizing more advance warning signs. Contractors should be obliged to use flaggers.	5
4. The number of TTC signs should be reduced to avoid overloading the area, getting overlooked, having orange barrage. Otherwise, flashing ones could be utilized.	4
5. Truck Mounted Attenuators (TMAs) are very effective TTC especially for laying out work zones. They ensure the safety of construction workers.	4
6. Road Construction Ahead (RCA) signs should be installed 5 miles in addition to the current RCA sign at 3 miles ahead and flashing lights, if added, would make it more visible.	2
7. Strict inspection and enforcement of traffic control functionality should be in place while penalties should be assigned if improperly maintained or malfunctioning TTC exist.	3
8. Message boards should be placed at distances 5, 3, and 1 mile approaching work zones.	1
9. The sign for speed reduction ahead should be bigger than the current one.	1
10. A construction vehicle should follow the work crew on front to protect them from any encroaching vehicles.	1

5.6.5 Other Recommendations

This section presents a set of general recommendations suggested by IDOT resident engineers to improve work zone safety performance. The general recommendations and the corresponding number of IDOT engineers who recommended it are presented in Table 5.12.

Table 5.12 IDOT Resident Engineers General Recommendations

Other Recommendations to Improve Work Zone Practices	Number of IDOT Engineers Providing Recommendations
1. More emphasize on work zone hazard education should be encouraged through examples/visits during driving education classes. This would make the traveling public pay more attention to driving and consequences of offenders.	3
2. Contractors need to send out bigger crews so that there is protection for the workers laying out and placing the devices and to accelerate the completion of layouts	2
3. Earlier announcements in the newspapers and TV would make the travelling public more aware of what is going to happen in the area.	1
4. Cell phones should be outlawed.	1
5. Contractors who fail to provide directed traffic control or correct deficient traffic control should be penalized.	1
6. Cameras could be used to view different construction sites to see what type of accidents are occurring while the data could be studied to prevent future accidents in similar types of construction zones.	1

5.7 RECOMMENDATIONS OF IDOT ENGINEERS TO UTILIZE INNOVATIVE TRAFFIC CONTROL DEVICES

This section presents the results of the second question of the survey in which IDOT resident were asked to provide their suggestions for innovative work zone traffic control devices that can minimize work zone crashes. Responses have been received from 72 resident engineers. This section presents a tabulated summary of their answers, as shown in Table 5.13(A) and Table 5.13(B) while the actual responses are listed in Appendix D.

Table 5.13(A) IDOT Resident Engineers Recommendations to Utilize Innovative Traffic Control Devices

Recommendations to Use Innovative Traffic Control Devices (1)	**Number of IDOT Engineers Providing Recommendations**
1. More effective and efficient use of state police enforcement patrols is important while designing a safe area to park behind the concrete barriers shooting their radar will help police officers doing their job.	17
2. Digital message boards with correct information should be properly placed prior and within work zones giving motorists alternative routes information, changing roadway conditions, and explaining possible hazards.	15
3. Digital speed displays should be utilized to provide speed indications for the motorists' current speed. It should be used approaching work zones and throughout the active area if it is lengthy	10
4. Automated photo enforcement of speeding violations should be widely adapted.	7
5. The new reflective sheeting panels/tapes have proved to be effective for nighttime traffic control. It would reduce the number of batteries that are land filled. Moreover, it is more brighter, consistent and would need no maintenance	4
6. Mini cones/barrels "Grabber Cones by Lakeside Plastics" in urban areas with narrow lanes should be utilized since it is effective, small, and has been already used in states such as Iowa and Indiana.	4
7. The use of flaggers should be enforced while making them more visible by placing a flashing light on their stop/go paddle. Moreover, the flagger should have a "boat horn" to warn workers when there is an emergency.	4
8. The usage of mobile maneuverable temporary barriers would provide good protection to construction workers since it can be used in many applications.	4

Table 5.13(B) IDOT Resident Engineers Recommendations to Utilize Innovative Traffic Control Devices

Recommendations to Use Innovative Traffic Control Devices (2)	**Number of IDOT Engineers Providing Recommendations**
1. Temporary rumble strips should be used prior and within construction zones to keep drivers' attention that something is approaching.	3
2. Arrowcades/arrow-boards are very useful if they are facing the right direction.	3
3. Truck Mounted Attenuator (TMAs) should be used for any moving operations to ensure worker's safety.	2
4. A sign of "Be Prepared to Stop" should be added to the other advance warning signs to minimize rear-end crashes.	2
5. Offering a suggested route on a website / message board / radio / media outlet would reduce traffic volume.	2
6. Barrier walls and crash walls are effective to prevent vehicles intruding work zones.	1
7. There is no need to have lights in traffic control devices in urban areas with overhead street lights along the roadway since the overhead street lights provide amble ambient light.	1
8. It might be good to use a red/white/blue strobe light on construction vehicles or allow the police to use IDOT vehicles.	1
9. Arrowcades on the interstate should be replaced with other TTC devices since drivers of big trucks cannot pay attention to them.	1
10. Barricades Type III should be utilized	1
11. Drone trooper police cars even with "dummy cops" in the seat may work as police presence.	1
12. Portable flags signals would greatly increase the flags visibility.	1
13. Bigger light bars on any vehicles within construction zones should be used.	1
14. Drums should be used more frequently than cones since it is bigger.	1
15. Penalties and fines on contractors should be assigned if they leave the jobsite and their traffic control in a mess.	1
16. The spacing configuration of the barricades, drums, or cones should be reduced especially on highway construction.	1
17. The use of the green vests in rural areas should be prohibited. The bright orange shirt works much better.	1

5.8 PLACEMENT OF TEMPORARY RUMBLE STRIPS WITHIN WORK ZONE LAYOUT

This section presents IDOT engineers' recommendations for the best location to place temporary rumble strips within work zones. Table 5.14 presents the recommended locations and the number of IDOT resident engineers supporting these locations.

Table 5.14 Placement of Temporary Rumble Strips within Work Zones

Placement of Temporary Rumble Strips within Work Zone Layout	**Number of IDOT Engineers Providing Recommendations**
1. As close to the work zone as possible, 500 feet prior to the flagger	26
2. Prior to "Road Construction Ahead" warning sign (current IDOT standard)	24
3. By the "Work Zone Speed Limit" sign	14
4. 1500 feet before lane closure taper at "Lane Merge" sign	12
5. Along tapers at the edge of work zones	5
6. 500 feet past the farthest estimated queue of stopped or slowed vehicles for work zones where stopped or significantly slowed traffic is expected.	3
7. At "Road Construction 1 Mile Ahead"	2
8. Use a note signaling to motorists that there is a hazard ahead	2
9. At "Road Construction 0.5 Mile Ahead"	1

As shown in Table 5.14, almost 30% of resident engineers recommended locating a set of temporary rumble strips as close to the work zone as possible. Many resident engineers reported that placing temporary rumble strips very close to work zone will help alert motorists encroaching construction zones to slow down or stop. Other significant percentage of resident engineers 27% recommended following the IDOT standard by having sets of temporary rumble strips in advance of work zone prior to "Road Construction Ahead" sign. The auditory and vibratory stimulus of temporary rumble strips will increase motorists' attention to follow work zone directions and regulations. Other resident engineers (14%) recommended placing rumble strips by "Work Zone Speed Limit" sign so that drivers will read the speed limit sign and slow down at work zones, while other resident engineers (14%) would like to have it 1500 feet before lane closure taper at "Lane Merge" sign as a reminder to motorist of the upcoming hazards. Three resident engineers reported the need to use traffic simulation programs to determine average expected queuing and based on the analysis, temporary rumble strips would be placed 500 feet past the farthest estimated queue of stopped or slowed vehicles.

5.9 CONCERNS ABOUT USING TEMPORARY RUMBLE STRIPS WITHIN WORK ZONES

The survey results show that 84% of IDOT resident engineers who responded to the last question of the survey reported many potential safety benefits for implementing temporary rumble strips in work zones. Despite this majority agreement, a number of concerns were raised by 10 resident engineers regarding the implementation of temporary rumble strips within work zones. Their concerns are summarized as follows:

1- People seem to ignore rumble strips during long durations of construction.
2- Temporary rumble strips may not be practically placed and removed in staged projects and may create future conflicts with the live lanes of traffic.
3- Maintenance of temporary rumble strips may be a big concern.
4- Rumble strips may stack along the fence and be hard to pick up.
5- Temporary rumble strips may be hard to keep down.
6- The travelling public may avoid and drive into the other lane or it may cause panic and accidents.

7- Residents and property owners may complain because of the noise it generates.

8- It could cause rear-end accidents by people slowing down before they go over them.

CHAPTER 6

OPTIMAL WORK ZONE SETUP FOR HIGHWAY CONSTRUCTION AND MAINTENANCE PROJECTS

6.1 INTRODUCTION

Many of short and long-term highway construction and maintenance projects on multi-lane highways require the closure of one or more lanes along the length of the work zone. This reduction in roadway capacity results in congestions and traffic delays causing drivers dissatisfaction and high road user delay costs (Schonfeld and Chien 1999; and Zhu et al. 2009). Moreover, a recent study reported an increasing trend of traffic deaths and injuries in and around highway work zones during the peak summer work season every year (NCHRP 2005). The aforementioned analysis of work zone crashes (Chapters 3 and 4), and the results of the survey of work zone practices (Chapter 5) also showed that work zone safety is significantly affected by work zone layout parameters such as work zone segment length, work zone operation hours, operating speed limit, type of temporary traffic control (TTC), and type of median barriers. Accordingly, the planning of short and long-term setup of highway construction projects is a crucial task that needs to be carefully performed and optimized in order to minimize agency cost and user delay cost while maximizing public and workers safety (Hajdin and Lindenmann 2007).

Computer simulation programs such as QUEWZ, *Queue and User Cost Evaluation of Work Zones*, (Memmott and Dudek 1984), and Quick Zone delay estimation program (Mitretek 2000) are used to determine the freeway work zone capacity and to estimate the motorists' queue delays associated with different transportation management plans alternatives. These programs however do not provide any optimization capabilities to estimate the optimum work zone setup of highway construction projects (Jiang and Adeli 2003). McCoy and Mennenga (1998) developed a framework to estimate the optimum work zone segment length that minimizes total work zone costs in a rural four-lane highway with one lane closure. User delay costs were modeled based on average daily traffic (ADT) volumes, while the accident cost was estimated based on a constant accident rate per vehicle mile. An optimum work zone length was derived based on yearly data that would be modified based on the annual unit cost factors.

In another study, Chien and Schonfeld (2001) developed a mathematical model to optimize work zone lengths on four-lane highways where one lane in one direction was closed. The model was formulated using the aforementioned framework (McCoy and Mennenga 1998) to generate an optimal solution based on user specified data such as work zone capacity, number of accidents per 100 million vehicle hour, user delay costs, and construction costs. One of the main limitations of the above two models is their assumption that there is a constant ADT on the highway which is not always accurate due to the traffic flow fluctuations throughout the day especially during morning and afternoon peak hours. To overcome this limitation, Jiang and Adeli (2003) developed another model that optimizes short-term work zone traffic delay using average hourly traffic data and considering the starting time of the work zone. The model considered the effect of nighttime construction on increasing construction costs and the probability of crash occurrence. Based on similar user specified inputs to the previous study by Chien and Schonfeld (2001), the global optimum work zone segment length was derived using simulated annealing neural network approach. The optimal work zone segment length was then calculated for different starting times through the day.

Despite the contributions of the aforementioned work zone optimization models, they still have a number of limitations, including their inability to consider: (1) other significant work zone decision variables such as work zone speed limit, type of temporary traffic control (TTC) measures, and barrier type as they focused only on the two decision variables of work zone segment length and starting time; (2) the impact of work zone speed limit, highway free flow speed, and type of construction activity on work zone capacity as they considered it as a separate input data; (3) the traffic risks caused by work zones and the combined impact of their setup parameters on the probability of crash occurrence; and (4) the impact of the total project length on the optimization procedure as they focused only on one day short-term construction projects which limits the applicability of the model.

The objective of this chapter is to present the development of a novel optimization model for work zone setup of highway construction projects that is designed to circumvent the aforementioned limitations of existing models. As shown in Figure 6.1, the model is designed to find an optimal solution for five main work zone decision variables: work zone segment length, work zone speed limit, starting time, type of TTC, and barrier type. The model provides the capability of minimizing the total work zone cost of short- and long-term highway work zones which integrates agency cost, user delay cost, and crash cost, as shown in Figure 6.1. A single-objective Genetic

Algorithm (GA) module (see Figure 6.1) is incorporated in the optimization model to solve this mixed real-integer cost optimization problem. The following three main sections in this chapter focus on (1) model formulation including its decision variables, objective function and cost metrics; (2) model implementation; and (3) performance evaluation including an application example.

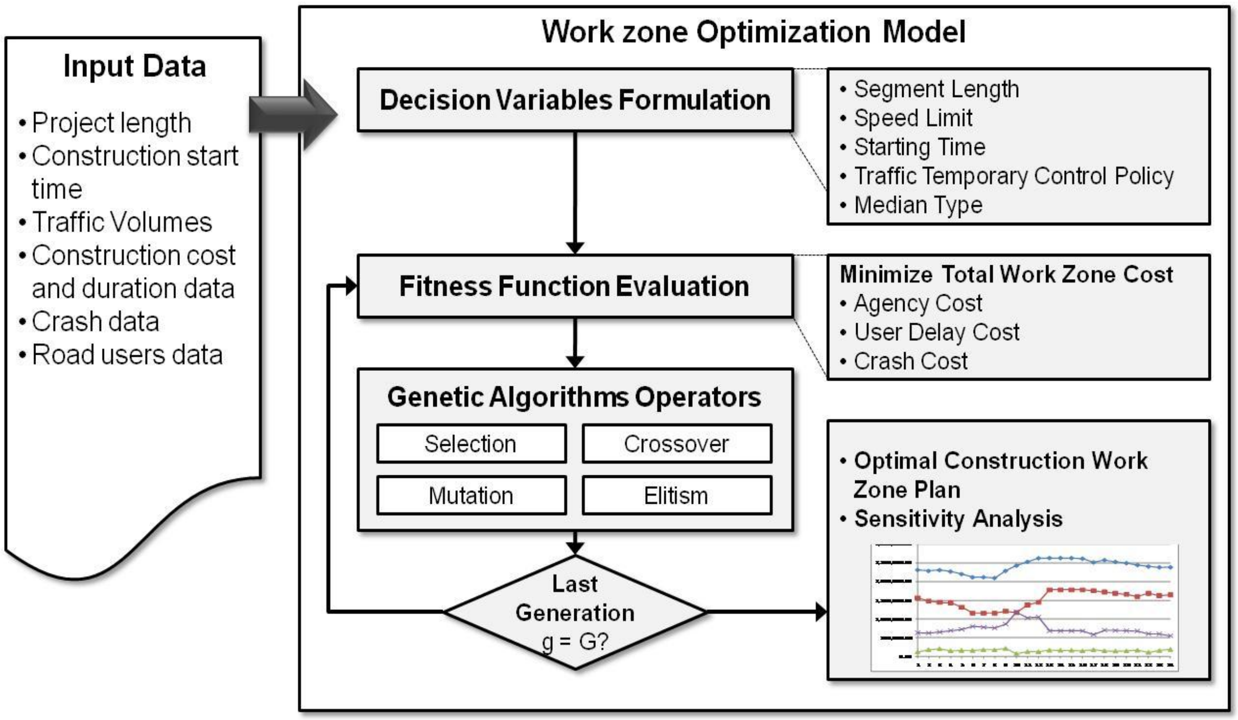


Figure 6.1 Work zone optimization model

6.2 MODEL FORMULATION

The optimal work zone setup model is formulated to identify the optimal setup of construction or maintenance work zones in order to minimize their total costs. The total cost of work zone is designed in this model to include agency cost, user delay cost, and crash cost. The following sections in the model formulation focus on: (1) the decision variables used to model work zone setup; and (2) the objective function including its three main metrics for calculating agency cost, user delay cost, and crash cost.

6.2.1 Decision Variables

The main decision variables in this optimization model are identified based on the findings of the aforementioned literature review (Chien and Schonfeld 2001; and Jiang and Adeli 2003) and the completed analysis of work zone crashes (Chapters 3 and 4), and the results of the survey of work zone practices (Chapter 5). The identified main decision variables in this optimization model are: (1) work zone segment length; (2) work zone speed limit; (3) construction starting time; (4) type of TTC; and (5) barrier type, as shown in Figure 6.2. The following subsections provide a more detailed description of these five decision variables.

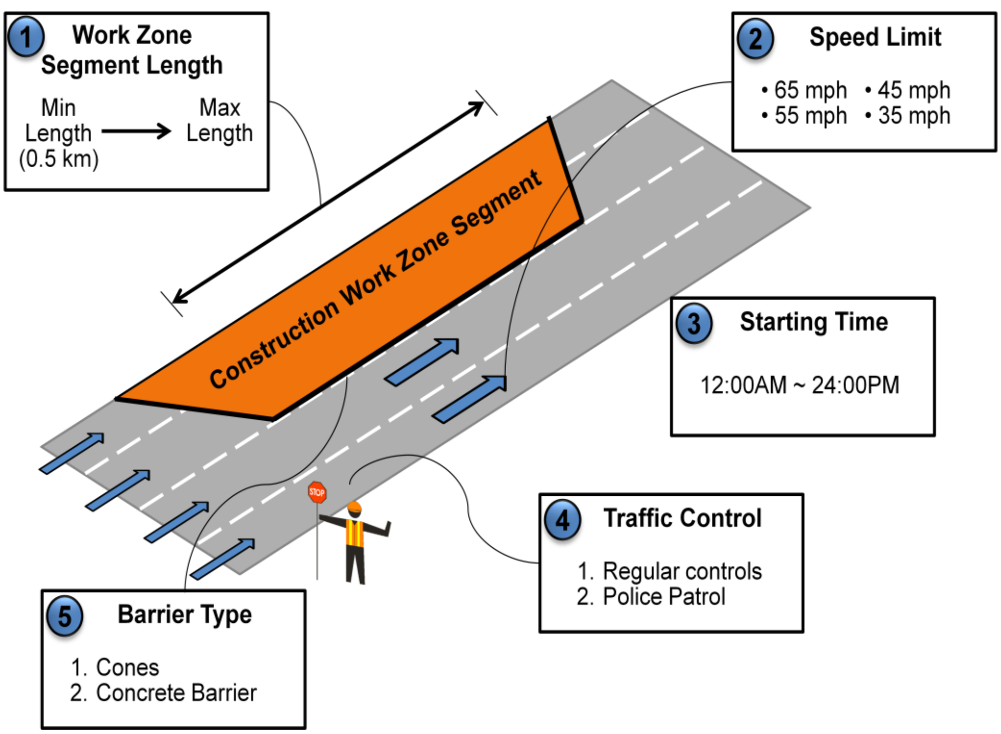


Figure 6.2 Work zone setup decision variables

1- Work Zone Segment Length

The first decision variable in this model is the work zone segment length. The use of a longer work zone segment improves the efficiency of construction operations, however it increases user delays. The minimum work zone segment length (SL) in a daily construction work area in this model is specified to be 0.5 mile and it can increase in increments of 0.1 mile. The maximum work zone segment length for a one day construction is determined similar to other available models (Chien and Schonfeld 2001; and Jiang and Adeli 2003) to be $SL_{max} = \frac{24 - a_3}{a_4}$, where a_3, a_4 represent the fixed setup time and average construction time per mile respectively. The number of possible work zone lengths (n) for a one day construction is calculated as $n = \frac{SL_{max} - 0.5}{0.1}$.

2- Work Zone Speed Limit

The second decision variable is work zone speed limit, which has four possible values of 35, 45, 55, and 65 miles per hour (mph). The first three values are chosen to comply with the speed limits that are mostly enforced at construction work zones while the fourth represents a work zone “with no speed reductions”. Work zone speed limit has a direct impact on both user delay costs and crash costs. Reduced work zone speed limits restrict work zone capacity, which leads to longer queues and higher user delay costs. On the other hand, reducing speed limits leads to a reduction in crash costs as the frequency of crash occurrence was found to be statistically correlated with work zone speed limit in Chapter 4. Moreover, the survey results discussed in Chapter 5 showed that work zones with high operating speed limits or “no speed reductions” are considered to be more prone to encounter crashes than those with low speed limits.

3- Starting Time

The model assumes that construction or maintenance work can start at any time of the day and accordingly the starting time/hour of a work zone can take any value between 1 and 24. The starting time along with work duration affect the three work zone cost metrics. A starting time at 8:00 am will not require additional construction cost compared to a starting time at night. This 8:00 am starting time however requires working during the morning hours of high traffic flow, which leads to an increase in user delay costs. Similarly, the crash cost is affected by the starting time. For example, scheduling the work zone operations during afternoon and/or evening hours (4pm ~ 8pm) increases the risk of crash occurrence compared to daytime construction (10am ~ 4pm) based on the findings of the completed survey in Chapter 5.

4- Temporary Traffic Control (TTC) Type

The fourth decision variable represents the type of the TTC utilized in the work zone. In this model, two types of TTC are considered: (1) regular TTC controls only; and (2) both police patrols and regular TTC controls. The use of police traffic patrols in construction and maintenance work zones is proved to be effective in increasing drivers' attention and compliance with work zone regulations (MSHA 2005). On the other hand, the use of police setup patrols causes an increase in construction cost, especially for long term work zones.

5- Barrier Type

In this model, the fifth decision variable represents the barrier type that is used to separate the public traffic from the construction area and workers. This decision variable in the model has two possible alternatives: (1) regular barriers; and (2) temporary concrete barriers. Temporary concrete barriers are sets of freestanding, precast, concrete segments typically 10 feet in length with built-in connection devices. The use of temporary concrete barriers reduces the risk level of crash occurrence (Chapter 5), however it causes an increase in the construction cost.

6.2.2 Objective Function

The objective function in this model is designed to minimize the total work zone cost which incorporates: (1) agency cost; (2) user delay cost; and (3) crash costs over the entire project duration, as shown in Eq. 6.1.

$$C_T = C_a + C_u + C_c \tag{6.1}$$

Three new cost metrics are developed and incorporated in this model to estimate these three cost components. The following subsections describe the formulation of these metrics.

1- Agency Cost Metric

The agency cost of a work zone is formulated in this model to include: (1) setup and removal costs; (2) construction/maintenance cost per work zone mile per lane; (3) overtime cost if work will extend beyond regular working hours (6:00am~4:00pm); (4) additional cost if police patrols will be hired during construction operations; and (5) extra cost if temporary concrete barriers will be used. The average agency cost C_a (see Eq. 6.2) represents the total agency cost for maintaining/constructing a work zone of segment length SL repeated through a number of days $nZones$ to account for long-term work zones.

$$C_a = \alpha_{time} \text{ x } \alpha_{TTC} \text{ x } \alpha_{barrier} \text{ x } (a_1 + a_2 \; x \; SL) \text{ x } nZones \qquad \$/project \tag{6.2}$$

Where, α_{time}, α_{TTC}, and $\alpha_{barrier}$ = cost modification factors that account for the construction time, the type of temporary traffic control, and the use of temporary concrete barriers respectively; a_1 = fixed setup and removal cost independent of work zone length; a_2 = average construction/maintenance cost per work zone lane mile; SL = segment length of work zone per one day construction; and $nZones$ = number of work zone segments required to complete the whole project operation of total length L which can be calculated as $\left(nZones = \frac{\text{L}}{SL}\right)$.

The first cost modification factor α_{time} represents the overhead costs that accounts for additional overhead costs, overtime labor premium wages and reduced worker productivity during overtime hours. The model is designed to enable construction planners to input this data to specify the impact of overtime hours on construction cost as shown in Table 6.1. The construction cost in this model is calculated on an hourly basis that accumulates daily hourly costs.

Table 6.1 Example of Hourly Time Modification Factor

Working Hour	α_{time}	Working Hour	α_{time}
1:00 AM	2	13:00	1
2:00	2	14:00	1
3:00	2	15:00	1
4:00	2	16:00	1.5
5:00	2	17:00	1.5
6:00	1	18:00	1.5
7:00	1	19:00	1.5
8:00	1	20:00	2
9:00	1	21:00	2
10:00	1	22:00	2
11:00	1	23:00	2
12:00	1	24:00	2

The second modification factor α_{TTC} represents the extra cost associated with using different types of temporary traffic controls in construction work zones. Only police setup patrols are considered in this model to cause an increase in construction costs compared to other regular temporary traffic control measures. According to FHWA, freeway service patrol (including administration cost, contingency and patrol dispatch) costs approximately $120/hr (FHWA 2008). The model is designed to enable construction planners to input this data to specify the extra cost of utilizing police patrols as shown in Table 6.2. For example, an increase of 1.2% of total construction cost can be estimated if police patrol services are hired for the whole construction/maintenance work duration.

Table 6.2 Example of Temporary Traffic Control Modification Factor

Temporary Traffic Control Type	α_{TTC}
Regular Countermeasures	1
Hiring Police Patrol Services	1.012

The third modification factor $\alpha_{barrier}$ represents the extra cost associated with using temporary concrete barriers in construction work zones. Temporary concrete barriers are sets of freestanding, precast, concrete segments typically 10 feet in length with built-in connection devices. According to FHWA, temporary concrete barriers unit will roughly cost $15/linear foot (FHWA 2008). The model is designed to enable construction planners to input this data to specify the extra cost of utilizing temporary concrete barriers as shown in Table 6.3. For example, an increase of 10% of total construction costs can be estimated if temporary concrete barriers are utilized, as shown in Table 6.3.

Table 6.3 Example of Barrier Modification Factor

Temporary Concrete Barrier	$\alpha_{barrier}$
No Barrier	1
Temporary Concrete Barrier	1.1

2- User Delay Cost Metric

Highway construction usually causes traffic congestions and hazardous conditions for the traveling public. These traffic congestions create user delay costs for the travelling public due to the reduction of work zone capacity that results in reducing travel speed and increasing travel time (Zhu et al. 2009). Motorists' delay costs can be expensive and it may exceed the maintenance expenditures by highway agencies (Chien and Schonfeld 2001). The user delay cost consists of: (1) the moving delay cost through work zones that results from the reduced speed in a work zone; and (2) the queue delay cost when approaching traffic flow Q exceeds the work zone capacity C_w (Schonfeld and Chien 1999). The accuracy of estimating the moving and queue delay costs depends on the accuracy of work zone capacity, C_w. In this model, work zone capacity C_w is calculated based on the work zone operating speed U_o and using the model developed by Benekohal et al. (2003). Work zone operating speed U_o in that model is calculated based on work zone free flow speed (FFS) and the speed reduction due to work zone intensity (R_{WI}) (Benekohal et al. 2003). Work zone free flow speed FFS is assumed in this model to exceed work zone speed limit SP (decision variable) by 5 mph. The speed reduction due to work zone intensity R_{WI} in this model was estimated to be 12.82 mph assuming that the number of workers in the active work area is 4; the number of equipment in active area is 2; and the distance between the active work area and the open lane is 4 feet. In this model, work zone operating speed U_o is simplified to be a function of work zone speed limit (see Eq. 6.3), and work zone capacity C_w as a function of work zone operating speed U_o (see Eq. 6.4).

$$U_o = SP - 7.82 \qquad mph \tag{6.3}$$

$$C_w = 128.2\ x\ U_o{}^{0.6857}\ vph \tag{6.4}$$

The user delay cost metric estimates costs dynamically on an hourly basis. If the approaching hourly traffic volume (Q) is less than or equal work zone capacity C_w , no queue will formulate and time delay t_d will only be due to the moving delay t_m. The moving delay per hour is calculated using Eq. (6.5) assuming an average approaching speed of 65 mph.

$$t_d = t_m = \left(\frac{1}{U_o} - \frac{1}{65}\right) x\ Q\ x\ SL \qquad vehicle.hour/hour \qquad if\ \ Q \leq C_w \tag{6.5}$$

On the other hand, if the approaching hourly traffic volume (Q) is greater than work zone capacity C_w, queue will formulate and time delay t_d will be due to moving delay t_m and queue delay t_q. The moving delay in this case is calculated using Eq. 6.6 and the queue delay is calculated using Eq. 6.7 (Chien and Schonfeld 2001). The freeway capacity without work zone C_0, is a constant number. Time delay t_d is calculated using Eq. 6.8.

$$t_m = \left(\frac{1}{U_o} - \frac{1}{65}\right) x\ C_w\ x\ SL \qquad vehicle.hour/hour \qquad if\ \ Q > C_w \tag{6.6}$$

$$t_q = 0.5\ x \left(1 + \frac{Q - C_w}{C_0 - Q}\right) x\ (Q - C_w) \qquad vehicle.hour/hour \qquad if\ \ Q > C_w \tag{6.7}$$

$$t_d = t_m + t_q \tag{6.8}$$

The duration required to complete a work zone segment, D, is calculated as shown in Eq. 6.9 where a_3, a_4 represent the fixed setup time and the construction time per mile, respectively.

$$D = a_3 + (a_4\ x\ SL) \qquad hour \tag{6.9}$$

The accumulated time delay T_d for one day construction is the summation of hourly time delays given a starting construction time t and summing over $(t + D)$ as shown in Eq. 6.10. The user delay cost is the multiplication of the accumulated time delay T_d and the average user delay cost per hour c_d (can be estimated using the department of transportation data (IDOT 2000)) by the number of work zone segments of the whole project $nZones$ as shown in Eq. 6.11.

$$T_d = \sum_t^{t+D} t_d \qquad vehicle.hour \tag{6.10}$$

$$C_u = T_d \; x \; c_d \; x \; nZones \qquad \$/project \tag{6.11}$$

3- Crash Cost Metric

Konovo (2005) reported that the annual cost of work zone crashes in the United States exceeded $4 billion. Existing models used a crash cost metric for work zones that is similar to the one used for freeway sections. This assumption underestimates work zone crash costs because it does not consider the increased hazardous conditions around work zones compared to other uninterrupted freeway sections. In order to overcome this limitation of existing models, this model incorporates a new crash cost metric for work zones that is based on the findings of the analysis of work zone crashes (Chapters 3 and 4), and the results of the survey of work zone practices (Chapter 5). A novel equation was developed in Chapter 5 (Section 5.5) to quantify the impact of work zone layout parameters and the type of temporary traffic control measure on work zone crash cost as shown in Eq. 6.12.

$$C_c = \beta_{time} \, \mathrm{x} \, \beta_{TTC} \, \mathrm{x} \, \beta_{barrier} \, \mathrm{x} \, \beta_{speed} \, \mathrm{x} \, n_a \, \mathrm{x} \, v_a \, \mathrm{x} \, \mathrm{L} \, \mathrm{x} \, (1.05)^{nZones} \qquad \$/project \tag{6.12}$$

Where, β_{time} = probability of crash occurrence associated with the time of the day; β_{TTC} = effectiveness of TTC measures in work zones; $\beta_{barrier}$ = probability of crash occurrence if temporary concrete barriers are utilized; β_{speed} = probability of crash occurrence associated with different speed limits; n_a = number of crashes per work zone mile; v_a = average cost of work zone crash; L = project length; and $nZones$ = number of work zone setups during construction.

In Eq. 6.12, β_{time}, β_{TTC}, $\beta_{barrier}$, and β_{speed} are estimated based on the survey of work zone practices previously discussed in Chapter 5. The first crash cost modification factor β_{time}, is a time factor that represents the impact of construction hour on increasing the risk of crash occurrence. The model is designed to enable construction planners to input this data to specify the impact of working hours on increasing the expected monetary value of work zone crashes as shown in Table 6.4. IDOT resident engineers reported that afternoon construction (4pm ~ 8pm) increases the risk of crash occurrence by 20% when compared to daytime construction (10am ~ 4pm). Table 6.4 presents β_{time} values used in this model.

Table 6.4 Example of Time Modification Factor for Crash Cost

Working Hour	β_{time}	Working Hour	β_{time}
1:00 AM	1.15	13:00	1
2:00	1.15	14:00	1
3:00	1.15	15:00	1
4:00	1.15	16:00	1.2
5:00	1.15	17:00	1.2
6:00	1.21	18:00	1.2
7:00	1.21	19:00	1.2
8:00	1.21	20:00	1.2
9:00	1.21	21:00	1.15
10:00	1	22:00	1.15
11:00	1	23:00	1.15
12:00	1	24:00	1.15

The second crash cost modification factor β_{TTC} is a safety factor that reduces the probability of crash occurrence corresponding to specific TTC countermeasures. The model is designed to enable construction planners to input this data to specify the impact of TTC measures on reducing the expected monetary value of work zone crashes as shown in Table 6.5. Values of β_{TTC} used in this model are presented in Table 6.5.

Table 6.5 Example of Temporary Traffic Control Modification Factor for Crash Cost

Temporary Traffic Control Type	β_{TTC}
Regular Countermeasures	1
Hiring Police Patrol Services	0.16

The third modification factor $\beta_{barrier}$, is a safety factor that represents the probability of crash occurrence associated with the existence of concrete barriers along work zones. The model is designed to enable construction planners to input this data to specify the impact of barrier type on the expected monetary value of work zone crashes as shown in Table 6.6. According to survey results (Chapter 5), work zones with no concrete barriers are more prone (~30%) to encounter crashes compared with those that have temporary concrete barriers. Table 6.6 presents the values of β_{barrier} considered in this model.

Table 6.6 Example of Barrier Modification Factor for Crash Cost

Temporary Concrete Barrier	$\beta_{barrier}$
Regular Standard Barrier	1
Temporary Concrete Barrier	0.77

The fourth crash cost modification factor β_{speed} represents the probability of crash occurrence associated with work zone speed limit. Work zone speed limit was found to be statistically correlated with the frequency of work zone crashes (Chapter 4). The survey results showed that work zones with “no speed reductions” are more prone to encounter work zone crashes by approximately 53% compared to work zone of speed limit 35 mph (Chapter 5). The model is designed to enable construction planners to input this data to specify the impact of work zone speed on increasing the expected monetary value of work zone crashes as shown in Table 6.7. Values of β_{speed} used in this model are presented in Table 6.7. The average number of crashes per work zone mile n_a was calculated in Chapter 5 (section 5.5) to be 5 crashes per work zone mile. The average cost of work zone crash was estimated to be $44,131 per work zone crash.

Table 6.7 Speed Modification Factor for Crash Cost

Work Zone Speed Limit		β_{speed}
35 mph	56 kph	1
45 mph	72 kph	1.16
55 mph	88 kph	1.35
65 mph	104 kph	1.53

The total work zone cost is formulated by substituting equations 6.2, 6.11, and 6.12 into 6.1 to represent to the total project cost of construction/maintenance work zone shown in Eq. 6.13.

$$C_T = \alpha_{time} \text{ x } \alpha_{TTC} \text{ x } \alpha_{barrier} \text{ x } (a_1 + a_2 \; x \; SL) \text{ x } nZones + T_d \; x \; c_u \; x \; nZones + \beta_{time} \text{ x } \beta_{TTC} \text{ x } \beta_{barrier} \text{ x } \beta_{speed} \text{ x } n_a \text{ x } v_a \text{ x L x } (1.05)^{nzones} \quad \text{\$/project} \qquad (6.13)$$

The model estimates total work zone costs dynamically every hour and accumulates the total cost over the total construction duration. If the traffic volume (Q) is less than work zone capacity (C_w), Eq. 6.5 is used for calculating the hourly time delay in a work zone segment. On the other hand, if the traffic flow volume (Q) exceeds work zone capacity (C_w), queues will be created and equations 6.6, 6.7, and 6.8 are used to calculate the hourly time delay in a work zone segment.

6.3 MODEL IMPLEMENTATION

The optimization model was implemented using genetic algorithms (GAs) in a C++ object oriented environment. Genetic algorithms are search and optimization tools that assist decision makers in identifying optimal or near-optimal solutions for problems with large search space inspired by the mechanics of evolution (Goldberg 1989; and El-Rayes and Kandil 2005). The GA model was linked to a prototype database that was developed in Microsoft Access 2007 in order to facilitate the storage and retrieval of traffic volumes and cost modification data. The relational database contains eight tables that stores the following data: (1) 24-hour traffic volumes; (2) impact of construction time on agency cost (Table 6.1); (3) impact of TTC type on agency cost (Table 6.2); (4) impact of concrete barrier type on agency cost (Table 6.3); (5) impact of construction time on crash cost (Table 6.4); (6) impact of TTC type on crash cost (Table 6.5); (7) impact of concrete barrier type on crash cost (Table 6.6); and (8) impact of speed on crash cost (Table 6.7).

6.4 PERFORMANCE EVALUATION

In order to evaluate and refine the performance of the optimization model, an application example is analyzed to evaluate the performance of the developed optimization model and demonstrate its capabilities in optimizing work zone setup. In this example, a long-term work zone setup is selected to closely resemble that of an existing pavement highway maintenance project to enable examining the performance of the model in a real-life setting. The example involves the maintenance of a one-lane segment that has a length of 10 miles. This setup requires the closure of one lane along the length of the work zone while the other lane is open for travelling public. Vehicles approaching the work zone are assumed to be travelling at a free flow speed of 65 mph. The minimum work zone segment length in a one-day construction is chosen to be 0.5 mile. Continuous work operations are assumed, where roadway will be open for travelling public as soon as work operations are completed in each segment.

In this example, the present model is used to support construction planners in their search for an an optimal work zone setup that specifies: work zone segment length, work zone operating speed, operation starting time, temporary traffic control measure, and barrier type. The main optimization objective in this work zone setup problem is to minimize total work zone cost including: agency cost, user delay cost, and crash cost.

In order to optimize work zone setup in this application example, the present model requires construction planners to specify and input the following parameters: (1) impact of construction start time on agency cost (see Table 6.1); (2) impact of TTC on agency cost (see Table 6.2); (3) impact of barrier type on agency cost (see Table 6.3); (4) impact of construction start time on crash cost (see Table 6.4); (5) impact of TTC on crash cost (see Table 6.5); (6) impact of barrier type on crash cost (see Table 6.6); (7) impact of speed limit on crash cost (see Table 6.7); (9) total project length (see Table 6.8); (10) freeway capacity without work zone (see Table 6.8); (11) approaching free flow speed (see Table 6.8); (12) number of crashes per work zone mile (see Table 6.8); (13) average crash cost (see Table 6.8); (14) average user delay cost (see Table 6.8); (15) fixed setup and removal cost (see Table 6.8); (16) agency cost per mile (see Table 6.8); (17) fixed setup and removal time (see Table 6.8); (18) maintenance duration per mile (see Table 6.8); and (19) hourly traffic flow (see Figure 6.3). The approaching hourly traffic flow shown in Figure 6.3 was selected similar to the one used by Jiang and Adeli (2003). All of these values are intended to demonstrate the implementation and application of this model rather than to represent a specific site.

Table 6.8 Model Variables, Description, and Values

Input Parameters	Description	Values
L	Total project length	10 miles
C_o	Freeway capacity without work zone	2,600 vph
U_o	Approaching free flow speed	65 m/hr
n_a	Number of crashes per work zone mile	5 crashes/mile
v_a	Average crash cost	44,131 $/crash
c_d	Average user delay cost (IDOT 2000)	15 $/veh-h
a_1	Fixed setup and removal cost	1,000 $/zone
a_2	Average agency cost per mile	120,000 $/mile
a_3	Fixed setup and removal time	2 h/zone
a_4	Average construction/maintenance time per mile	6 h/mile

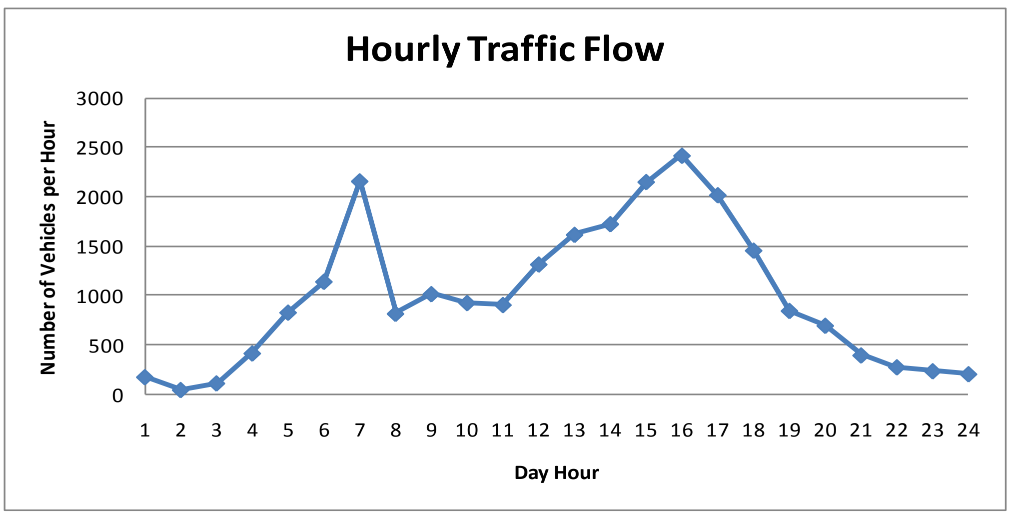


Figure 6.3 Expected hourly traffic volumes approaching a work zone

The model was used to analyze the above input data using varying genetic algorithm setups (e.g., population size, mutation rate, number of generations). These runs were able to generate a set of optimal work zone setups for different operation starting times, where each provides an optimal work zone setup and an associated minimum total work zone cost (see Table 6.9). The results in Table 6.9 show that police patrols were chosen for all different starting times in order to minimize crash costs while concrete barriers were chosen for all starting times except (6:00pm~ 9:00pm). Work zone segment length and operating speed varies with different operation starting times. Figure 6.4(a) and Figure 6.4(b) show the impact of various operation start times on the generated two optimal setup decision variables for work zone segment length and work zone operating speed, respectively.

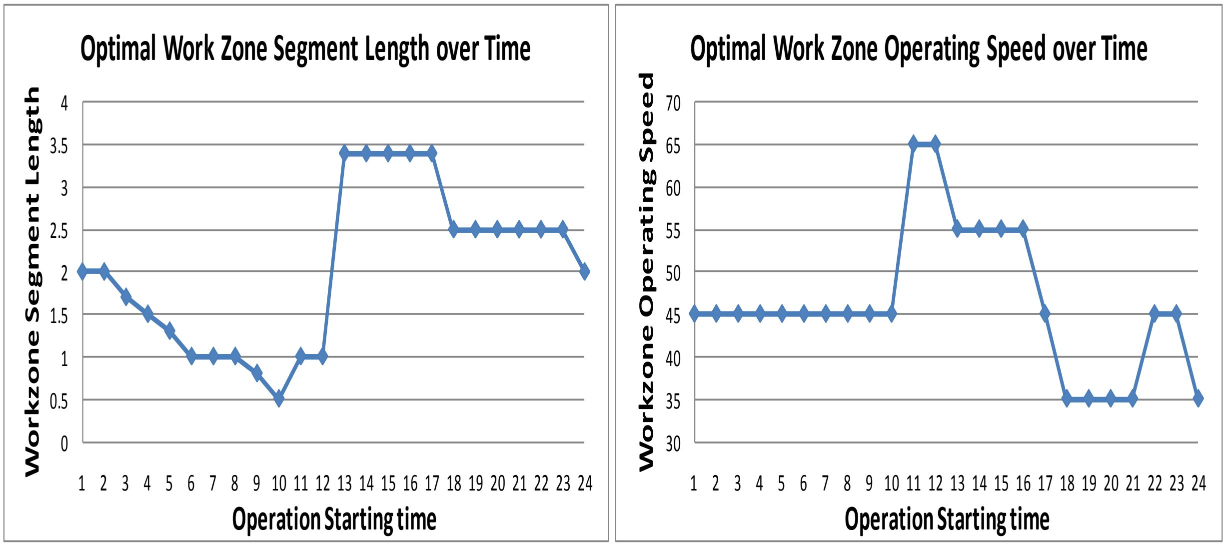
The results in Table 6.9 show that operation start times in the afternoon hours (2:00pm~5:00pm) cause the optimal work zone speed limit to increase to 55 mph. These optimal results are generated because of the high traffic volume (see Figure 6.3) during these hours which significantly increases the user delay cost. In order to control and minimize that increase in user delay cost, work zone speed limit needs to be increased to expand work zone capacity during these high traffic volume hours. On the other hand, if work operations are scheduled to start during evening hours (6:00pm~ 9:00pm), the optimal work zone speed limit was reduced to 35 mph to minimize crash costs.

The analysis of results presented in Table 6.9 shows that agency cost is at its minimum for regular operation starting time at 6:00am and it increases for other operation starting times. User delay cost does not vary significantly through different starting times although traffic volumes fluctuate significantly. This is explained due to changing work zone operating speed accordingly for different operation starting times as shown in Table 6.9. Crash cost varies with different operation starting times and it reaches its maximum value if operations start at 10:00am. This is explained due to choosing an optimal work zone segment of 0.5 mile where the total number of setups for a 10-mile project will be 20 setups. Crash cost increase exponentially with number of setups as shown in Eq. 6.12.

In this application example, the minimum optimal total work zone cost was found to be $2,098,600 when the optimal solution for the five main work zone setup variables is: (1) segment length of 1 mile, (2) speed limit of 45 mph; (3) starting time at 8:00am; (4) TTC of police patrols; and (5) use of temporary concrete barriers.

Table 6.9 Optimum Work Zone Setup for Different Starting Times

Operation Starting Time	Work Zone Segment Length	Work Zone Speed Limit	Type of TTC	Type of Barrier	Daily Const. Duration	Agency Cost	User Delay Cost	Crash Cost	TotalCost
1	2	45	Police Patrols	Concrete Barrier	14	1,562,280.00	120,273.00	633,073.00	2,315,620.00
2	2	45	Police Patrols	Concrete Barrier	14	1,480,050.00	181,879.00	626,982.00	2,288,910.00
3	1.7	45	Police Patrols	Concrete Barrier	12.2	1,446,720.00	208,111.00	656,166.00	2,311,000.00
4	1.5	45	Police Patrols	Concrete Barrier	11	1,431,430.00	149,494.00	691,736.00	2,272,660.00
5	1.3	45	Police Patrols	Concrete Barrier	9.8	1,321,320.00	161,349.00	723,271.00	2,205,940.00
6	1	45	Police Patrols	Concrete Barrier	8	1,158,300.00	159,914.00	801,760.00	2,119,970.00
7	1	45	Police Patrols	Concrete Barrier	8	1,158,300.00	179,705.00	782,714.00	2,120,720.00
8	1	45	Police Patrols	Concrete Barrier	8	1,158,300.00	176,634.00	763,668.00	2,098,600.00
9	0.8	45	Police Patrols	Concrete Barrier	6.8	1,208,350.00	216,120.00	865,142.00	2,289,610.00
10	0.5	45	Police Patrols	Concrete Barrier	5	1,172,600.00	76,335.50	1,181,880.00	2,430,820.00
11	1	65	Police Patrols	Concrete Barrier	8	1,375,480.00	126,462.00	1,028,780.00	2,530,730.00
12	1	65	Police Patrols	Concrete Barrier	8	1,447,880.00	126,305.00	1,052,710.00	2,626,890.00
13	3.4	55	Police Patrols	Concrete Barrier	22.4	1,782,220.00	166,015.00	683,346.00	2,631,580.00
14	3.4	55	Police Patrols	Concrete Barrier	22.4	1,782,220.00	165,042.00	683,346.00	2,630,600.00
15	3.4	55	Police Patrols	Concrete Barrier	22.4	1,782,220.00	164,692.00	683,346.00	2,630,250.00
16	3.4	55	Police Patrols	Concrete Barrier	22.4	1,782,220.00	150,242.00	683,346.00	2,615,800.00
17	3.4	45	Police Patrols	Concrete Barrier	22.4	1,756,760.00	176,815.00	582,687.00	2,516,260.00
18	2.5	35	Police Patrols	No Conc. Barrier	17	1,721,510.00	153,490.00	700,931.00	2,575,930.00
19	2.5	35	Police Patrols	No Conc. Barrier	17	1,690,760.00	143,582.00	693,847.00	2,528,190.00
20	2.5	35	Police Patrols	No Conc. Barrier	17	1,660,020.00	148,451.00	686,763.00	2,495,240.00
21	2.5	35	Police Patrols	No Conc. Barrier	17	1,598,540.00	167,534.00	679,680.00	2,445,760.00
22	2.5	45	Police Patrols	Concrete Barrier	17	1,690,760.00	109,117.00	606,407.00	2,406,290.00
23	2.5	45	Police Patrols	Concrete Barrier	17	1,623,130.00	159,088.00	601,630.00	2,383,850.00
24	2	35	Police Patrols	Concrete Barrier	14	1,644,500.00	188,808.00	551,004.00	2,384,310.00



(a) **(b)**

Figure 6.4 Work zone optimum setup over different operation starting times: (a) Optimal work zone segment length; and (b) Optimal work zone operating speed

6.5 SUMMARY AND CONCLUSIONS

This Chapter presented the development of a novel optimization model for work zone setup of highway construction projects that is designed to find an optimal solution for five main work zone decision variables: work zone segment length, work zone speed limit, operation starting time, type of TTC, and barrier type. The model provides the capability of minimizing the total work zone cost of short- and long-term highway work zones which integrates three new metrics developed to calculate agency cost, user delay cost, and crash cost. The three cost metrics were modeled to estimate work zone costs at each construction hour using an hourly traffic flow. The optimization model was implemented using genetic algorithms (GAs) in a C++ objected oriented environment. The GA model was linked to a prototype database that was developed in Microsoft Access 2007 in order to facilitate the storage and retrieval of traffic volumes and cost modification data.

In order to evaluate and refine the performance of the optimization model, an application example was analyzed. In this application example, a long-term work zone setup was selected to closely resemble that of an existing pavement highway maintenance project and involved the maintenance of a one-lane segment that has a length of 10 miles. For a light traffic flow of an average hourly traffic volume of 1000 vph, the minimum total work zone cost was attained for an optimum work zone setup of: (1) work zone segment length of 1 mile/day, (2) work zone operating speed of 45 mph; (3) operation starting time at 8:00am and continuing for 8 hours till 4:00pm; (4) police patrols present during work operations; and (5) temporary concrete barriers utilized at work zone. Police patrols and temporary concrete barriers were generated by the model for all global optimal solutions through different operation starting times while work zone segment length and operating speed varies accordingly with different operation starting times.

The results of the analyzed application example illustrate the contributions and new capabilities of the highway work zone optimization model including: (1) searching for and identifying optimal work zone setup solutions that specify segment length, operating speed, TTC policy, and concrete barrier at different operation staring times; (2) minimizing the total work zone.

CHAPTER 7

SETUP OF TEMPORARY RUMBLE STRIPS FIELD EXPERIMENTS

7.1 INTRODUCTION

Driver inattention can be due to a number of causes such as distraction, daydreaming, fatigue, drowsiness, and drug impairment (Griffith 1999). Rumble strips are one of the innovative countermeasures that are being installed along roadways that provide an auditory and vibratory warning to reduce run-off-the-road (ROR) crashes and to alert drivers to road conditions that require elevated alertness such as lane departures, changes in roadway environment, or approaching work zones (Fontaine and Carlson 2001; Meyer 2000; Miles and Finley 2007). This chapter presents: (1) a summary of rumble strips general specifications; (2) relevant research studies on rumble strips; (3) field experiment setup of temporary rumble strips; and (4) an evaluation of temporary rumble strips efficiency in terms of installation and removal processes of various types of different arrangements.

7.2 RUMBLE STRIPS GENERAL SPECIFICATIONS

Rumble strips can be classified as: (1) continuous permanent rumble strips; and (2) intermittent temporary rumble strips depending on the method of application and the goal (Meyer 2000). The continuous permanent rumble strips are mostly used on the shoulder of the road as a countermeasure for altering motorists to an unintentional lane departure (Neuman et al. 2003). These rumble strips are recessed below the pavement and are classified based on their installation method as milled or rolled. Most rumble strips in the United States are milled and the standard design is 7in. long, 12in. or more wide, 0.5in. deep, and spaced at 12 to 24 in. (Miles and Finley 2007). Several studies evaluated the safety effectiveness of continuous permanent rumble strips, and proved a reduction of more than 40% of vehicle crashes after the implementation of rumble strips (Griffith 1999). In Illinois, the standard characteristics of the continuous shoulder rumble strips are: (3 ft) width, (8 in.) spacing, and (0.75 in.) depth with an outside boundary of (12in.) from the edge of pavement (Griffith 1999).

On the other hand, the temporary intermittent type is mostly used over a short distance in different patterns intended to provide motorists with an increased perception of speed (Fontaine and Carlson 2001). These rumble strips consist of intermittent narrow, transverse areas of rough-textured or slightly raised road surface that extend along or across the travel lanes to alert drivers to any uncommon vehicular traffic conditions (Miles and Finley 2007). Several bundles of rumble strips are generally placed in different patterns in advance of a highway segment where reduced speed or elevated driver alert is desirable (Zech et al. 2005). Rumble strips patterns vary according to many factors such as pavement materials, type of rumble strips, location of wheel paths relative to rumble strips, and duration of temporary reallocation (Meyer 2000).

7.2.1 Temporary Rumble Strips Geometric Characteristics

The main geometric characteristics that differentiate various types of rumble strips include: (1) width, which is the distance along the rumble strips axis that runs perpendicular to the direction of vehicular traffic; (2) length, which is the distance along the rumble strips axis that runs parallel to the direction of vehicular traffic; (3) depth or height that is measured vertically from the top to the bottom of the rumble strips; and (4) spacing which is the distance between individual rumble strips that runs parallel to the direction of vehicular traffic, as shown in Figure 7.1 (Meyer 2000; Morgan 2003).

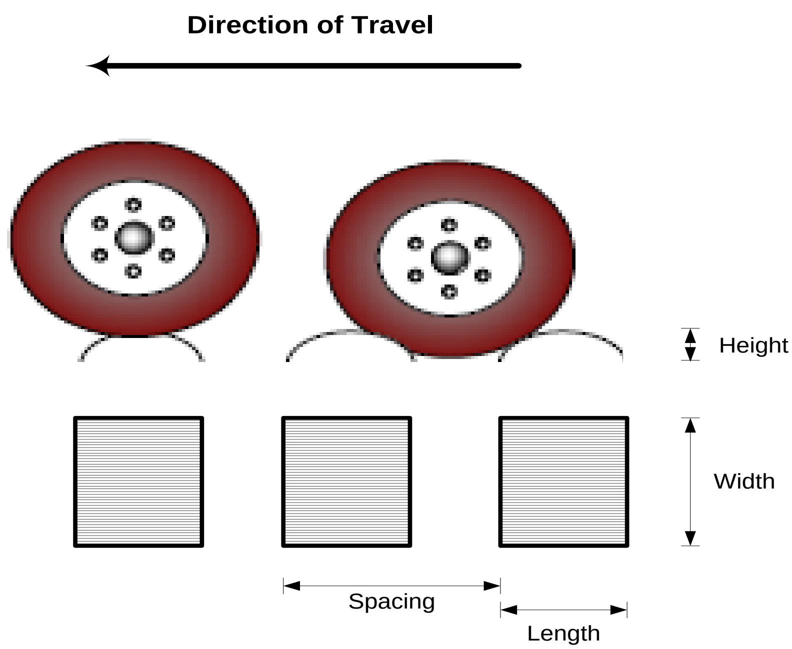


Figure 7.1 Rumble strips geometry

7.2.2 MUTCD Guidance for Rumble Strips

The Manual on Uniform Traffic Control Devices (MUTCD) provides guidance on the implementation of rumble strips. The main specifications of temporary rumble strips that are discussed in the manual are: (1) color; (2) spacing; (3) material; and (4) pattern. For rumble strips color, the Manual recommends the use of a color different than the color of the pavement for both the longitudinal and the transverse rumble strips (MUTCD 2003). Regarding the spacing intervals between transverse rumble strips, the Manual recommends that spacing may be reduced as the distance to the approaching conditions gets closer in order to convey an impression that the driving speed is too fast and/or that an action is imminent (MUTCD 2003). For the rumble strips material, the Manual recommends it not affect overall pavement skid resistance under wet or dry conditions. The Manual also recommends that the pattern be designed in a way that it should not promote unnecessary braking or erratic steering maneuvers by motorists (MUTCD 2003). Both longitudinal and transverse rumble strips can represent a real danger to bicyclists unless a minimum clear path of 4 ft (1.2 m) is provided at each edge of the roadway or on each paved shoulder (MUTCD 2003).

7.3 RESEARCH STUDIES ON RUMBLE STRIPS

Several research studies have been conducted to study the effectiveness of rumble strips and found that work zone safety improves when rumble strips are used (Meyer 2000; Morgan 2003). Other studies investigated the effect of rumble strips characteristics on the level of sound and vibration that motorists experience when they traverse rumble strips (Miles and Finley 2007). This section describes recent research studies on rumble strips and their main findings and organizes them in the following three main subsections: (1) rumble strips types; (2) rumble strips effectiveness; and (3) rumble strips characteristics.

7.3.1 Rumble Strips Types

A study was conducted by Zech et al. (2005) to evaluate the effectiveness of temporary rumble strips, and police presence combined with rumble strips. The study tested the effectiveness of two types of temporary rumble strips, 3M and Swarco which came in the form of tapes that glue to the pavement, and caused no damage to the actual pavement. In addition, they could be used multiple times, and required a short time for installation. The rumble strips had been tested on two interstate highways. The 3M rumble strips were 6 in. (152.4 mm) wide and 0.4 in (10.16 mm) thick installed in two sets, each set is in a length of 50 ft (15.25 m), comprised of six rumble strips spaced

10ft (3.05 m) apart. The Swarco rumble strips were made of black non-reflective high quality high carbon resin. Each rumble strip was 6 in. x 0.25 in. (152.4 mm x 6.35 mm) spaced 10ft (1.2 m) apart. Vehicle speeds were measured before and after the implementation of the speed control devices. The raw data files were analyzed by date, lane, and vehicle class. The study concluded that the 3M rumble strips were effective in reducing vehicles speed by approximately 2.4 mph (3.86 km/h), depending upon the lane closure setup. On the other hand, the Swarco rumple strips had partial success as it displayed no significant reduction of vehicle speeds.

Another study was conducted by Meyer (2000) to evaluate the effectiveness of (1/8 in.) thick temporary orange rumble strips versus the standardized (1/2 to ¾ in.) asphalt rumble strips at a bridge repair site in the State of Kansas. The study used one set of rumble strips consisting of 6 strips with (1 ft) spacing between strips. Strips were cut in (12-ft) segments. The rumble strips pattern was adjusted to include one set of three groups of strips, each comprised of six strips. Vehicle speeds were recorded with only the standard asphalt rumble strips in place as compared to those with the removable rumble strips. The qualitative analysis of the collected speeds showed that 6 strips per group were insufficient and the number needs to be increased to prove significant speed reduction. Although, the removable rumble strips were easily installed and removed, three of the strips detached from the pavement during the first week due to a significant amount of dirt and gravel beneath. The study reported that the orange removable rumble strips applied in this study had a positive effect on increasing motorists' awareness to an approaching work site, attributable to their high visibility that was consistent with the MUTCD recommendations for work zones.

7.3.2 Rumble Strips Effectiveness

Morgan (2003) conducted a study of work zones implementing rumble strips to compare the specifications used by the New York DOT with others. The main parameters were rumble strips thickness, spacing, color, problems associated with adhering to the pavement, and noise generated. Nineteen work zones with rumble strips were examined in the State of New York. Most of the applied rumble strips were installed using multiple layers of temporary pavement marking tape. All of the rumble strips were black to avoid any confusion that colored rumble strips may affect motorists. The study recommended the use of temporary rumble strips of 10 mm ± 3 mm thickness of different types, such as tapes and tread strips, in sets of six strips spaced at no more than 2.7 m apart and preferably at irregular variable intervals according to the speed limit.

In another study, Fontaine and Carlson (2001) investigated the impact of portable rumble strips on reducing speeds in rural maintenance work zones in the State of Texas. The main objectives of the study were to evaluate the usability of rumble strips for rural maintenance work zones, and to determine the direct impact on reducing the percentage of vehicles exceeding the speed limit. The rumble strips used in the experiment were precut 3.7-m (12-ft) long rolls. Each strip was (4in.) wide and (0.125 in.) thick. Six strips were used at each location spaced at (18 in.), and a weighted tamping cart was used to attach the strips to the pavement. Rumble strips were tested through four work zones that were two-lane low-volume, high-speed rural roads. Speed and traffic volume were measured for cars and trucks when normal work zone traffic control was set up, and when the experimental devices were installed. The implementation of the rumble strips showed a reduction in the percentage of passenger cars that exceeded the (70-mph) speed limit.

7.3.3 Rumble Strips Characteristics

The sound change that motorists experience when traversing rumble strips is based on the ability of a rumble strips design to convert kinetic energy effectively from vehicle tires into sound (Miles and Finley 2007). A recent study performed by Miles and Finley (2007) studied the impact of vehicle speed, vehicle type, pavement type, and rumble strips design on the level of sound change that motorists perceive when traversing rumble strips. The rumble strips characteristics considered in this study were the width, length, and spacing. The researchers considered increases of 4 dB or greater to be sufficient to alert drivers when they drive over rumble strips. Sound readings were taken from inside three different vehicles to study the different levels of stimulus experienced by a variety of drivers. The change in sound was measured using a sound meter and a data logger that was calculated as the difference before and after rumble strips condition. More than 400 test runs were performed within the three different vehicles at variable speed limits that ranged from 45 to 70 mph. The study results showed that rumble strips dimensions and applications greatly affected sound level changes, and recommended practitioners to consider all different design characteristics when choosing a specific rumble strips design.

7.4 FIELD EXPERIMENT SETUP OF TEMPORARY RUMBLE STRIPS

This section presents the setup of the field experiments that were conducted to evaluate the performance and practicality of three types of temporary rumble strips that are commonly used within and prior to highway construction zones. The tested types of temporary rumble strips are: (a) ATM of Advance Traffic Markings; (b) RoadQuake of Plastic System Safety; and (c) Rumbler of Swarco Industries Inc. These three types of temporary rumble strips have been tested using four vehicles: a sedan, a cargo van, a 26-ft truck, and a motorbike. A sound level meter has been used for measuring the auditory stimulus inside each vehicle when traversing each tested temporary rumble strips set. The following subsections present in more details the experimental setup and measuring procedure.

7.4.1 Site Preparation

The field experiments were conducted at a closed segment of an airport taxiway that is located in Rantoul, Illinois. This closed segment of the taxiway was rented from the Rantoul National Aviation Center for the duration of the experiments and is located parallel to the east-west runway, as shown in Figure 7.2. The taxiway has a length of 4300 feet and a width of 72 feet that can be divided into 6 equal lanes of 12 feet, as shown in Figure 7.3. This specific location was selected for the field experiments because (1) the taxiway's 4300-foot length provided adequate distance to bring the largest tested vehicles up to the required speed and safely decelerate it after traversing each set of temporary rumble strips, as shown in Figures 7.3 and 7.4; (2) the taxiway's 72-foot width allowed the research team to improve the efficiency of simultaneously setting up and testing various types of rumble strips and patterns; and (3) the taxiway can be closed to all types of traffic during the experiments to ensure the safety and accuracy of the conducted tests. In these experiments, temporary construction cones were used to clearly identify the taxiway lanes and specify directions of traffic flow. In addition, the construction cones were used to mark a grid on the concrete pavement surface of equally spaced points of 30 ft (see Figure 7.3) to enable a consistent pattern of reading sound measurements.

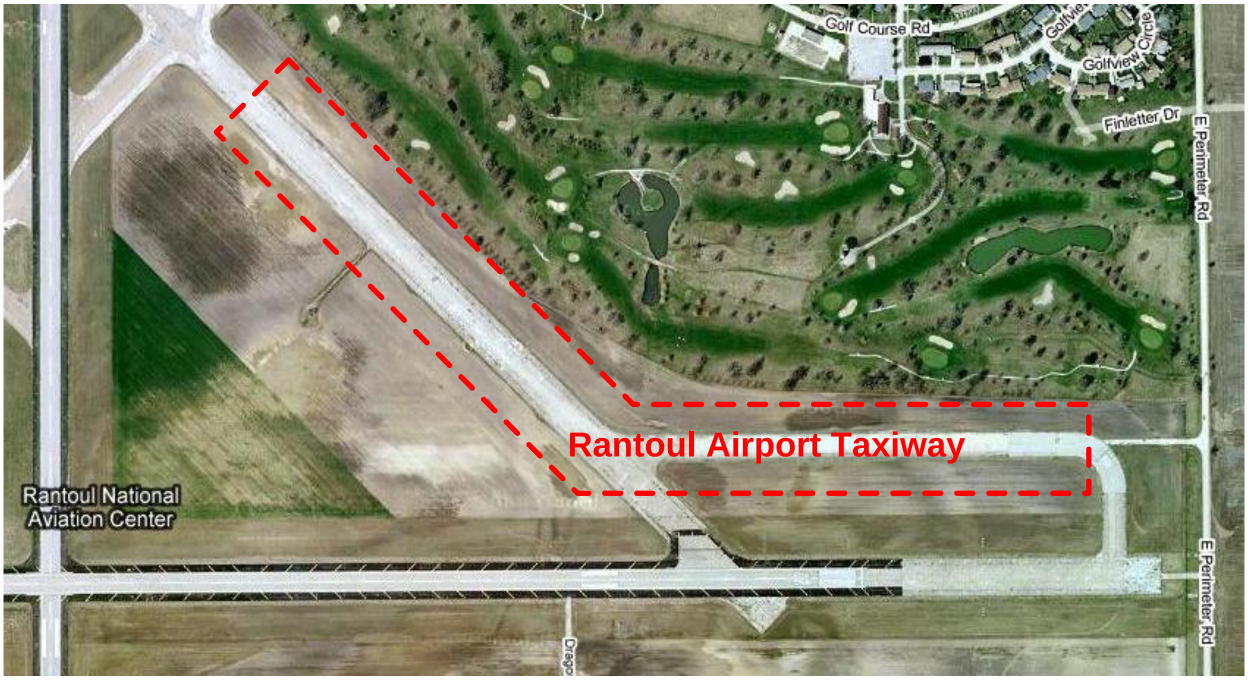


Figure 7.2 Satellite Overview of Rantoul Airport and the utilized taxiway for the experiments.


Figure 7.3 Site of field experiments showing tested sets of temporary rumble strips.

Figure 7.4 Site of field experiments showing the 26' truck traversing a set of rumble strips.

7.4.2 Tested Temporary Rumble Strips

The field experiments evaluated the performance of three types of temporary rumble strips of different manufacturers that are currently being used by other State Departments of Transportation (DOTs): (1) ATM of Advance Traffic Markings; (2) RoadQuake of Plastic System Safety; and (3) Rumbler of Swarco Industries Inc. The main objective of testing different types of rumble strips was to quantify the impact of these rumble strips material and dimensions on the generated sound levels. The following section discusses the basic characteristics of the three tested rumble strips.

1- ATM Removable Rumble Strips

ATM removable rumble strips are manufactured by Advance Traffic Markings. This type of temporary rumble strips is self-adhesive, having pre-applied adhesive to facilitate the installation process. ATM rumble strips are produced in various highly visible colors. The tested strips had a thickness of 0.25 inches and were packaged in rolls with 4 inches in width and 50 feet in length. In the field experiments, a total of four rolls were used and they were cut using a regular saw to produce the required 4 feet length for the tested rumble strips, as shown in Figure 7.5. The installation and removal processes of all rumble strips will be discussed in the next chapter.

Figure 7.5 Dimensions of the tested ATM rumble strips (4’long x 4” wide x 0.25” thick).

2- Swarco Removable Rumble Strips

The second type of temporary rumble strips tested was the “Rumbler” which is manufactured by Swarco Industries Inc. The tested strips had a thickness of 0.25 inches and were cut in segments, 6 inches wide x 4 feet long, as shown in Figure 7.6.

Figure 7.6 Dimensions of the tested Swarco rumble strips (4'long x 6" wide x 0.25" thick).

3- RoadQuake Temporary Portable Rumble Strips

The third type of temporary rumble strips tested was the RoadQuake temporary rumble strips which is manufactured by Plastic Systems Safety. These rumble strips are precut by the manufacturer at 11 feet long which traverses the entire lane as shown in Figure 7.6. These rumble strips are also wider and thicker than the previous two types. The dimensions of the tested strips are 11 feet long x 12 inches wide x 13/16 inches thick, as shown in Figure 7.7. Furthermore, the installation of this type of temporary rumble strips does not require fasteners or adhesives. The rumble is stable under its own weight as each strip weighs 105 lbs.

Figure 7.7 Dimensions of tested RoadQuake rumble strips (11'long x 12" wide x 13/16" thick).

7.4.3 Testing Vehicles

The field experiments utilized three different vehicles and a motorcycle to quantify the different levels of auditory stimulus experienced by motorists when traversing different patterns and types of temporary rumble strips. The three vehicles used were a sedan, a cargo van, and 26’ truck. The three vehicles are shown in Figure 7.8 along with the empty weight specification of each vehicle. The three vehicles were driven at speeds of 30, 40, and 50 mph along all the tested patterns of rumble strips. These testing speed values were chosen to comply with the speed limits that are mostly enforced at construction work zones in the State of Illinois. The 26- foot truck was driven by the research team and was tested over all designated temporary rumble strips patterns.

The tested motorcycle was a Harley Davidson Heritage Softail Classic collection and was also driven by a member of the research team, as shown in Figure 7.9. It should be noted that the motorcycle was tested in the field experiments to evaluate many concerns that have been raised about the impact of temporary rumbles on the safety of motorcycles including the potential risk that the rumble strips may cause them to overturn. During the field experiments, the motorcycle was safely driven by a member of the research team over the majority of the tested rumble strips at different speeds to subjectively evaluate the impact of these strips on the stability and safety of driving the motorcycle. The main findings of this subjective analysis indicate that the motorcycle can be safely driven over the tested temporary rumble strips arrangements without exposing the driver to the hazards of instability or overturning. The field experiments also attempted to evaluate the changes in sound levels that would be experienced by motorcycle drivers when they travel over temporary rumble strips. The sound level meter however could not record any significant increase in sound level readings when the motorcycle traveled over the tested temporary rumble strips because of the loud engine noise of the motorcycle. Accordingly, the analysis of the measured sound levels in the rest of this report will be limited to the aforementioned three vehicles: sedan, cargo van, and 26- foot truck shown in Figure 7.8.

Empty weight: 2,729 lbs	Empty weight: 5,227 lbs	Empty weight: 12,605 lbs
(1)	(2)	(3)

Figure 7.8 Study vehicles: (1) 2007 Ford Focus, (2) Cargo Van, and (3) 26-footTruck.

Figure 7.9 Study motorcycle (Harley Davidson Heritage Softail Classic).

7.5 EVALUATING THE EFFICIENCY OF TEMPORARY RUMBLE STRIPS

This section evaluates the efficiency of temporary rumble strips in terms of practicality and ease of use within and prior to work zones through the time and effort required during: (1) the installation process; and (2) the removal process.

7.5.1 Installation Process

The installation of the three temporary rumble strips was easy to implement on the experiment site. Air and surface temperatures during the experiment period were around 76~80ºF which complies with the manufacturers' recommendation for air and surface temperature to be 50ºF and rising. The research team first waited for 3 hours to ensure the surface dryness then the pavement surface was thoroughly cleaned of any debris such as sand, dirt, and loose aggregate using push brooms as shown in Figure 7.10. Other materials such as silt, and mud were removed.

Figure 7.10 Pavement surface cleaning.

The alignment of rumble strips were set out according to a pre-designed plan shown in Figure 7.11 that shows nine different patterns of rumble strips. First, all patterns of 8 rumble strips per set with different configurations were installed and tested. Sound readings were recorded for different vehicles traversing at different speed limits following the procedure described Chapter 8. Second, two strips of each rumble strips type were removed and patterns of 6 strips per set of different configurations were tested and sound readings were recorded. Finally, two more strips of each rumble strips type were removed and patterns of 4 strips per set were tested and sound levels were recorded. The alignment of rumble strips were performed using red chalk line, a tape measure, and three 12 feet lumber (1” x 4”) joists as shown in Figure 7.12. Each type of temporary rumble strips was installed based on the manufacturer’s recommendation which will be briefly discussed in the following sections.

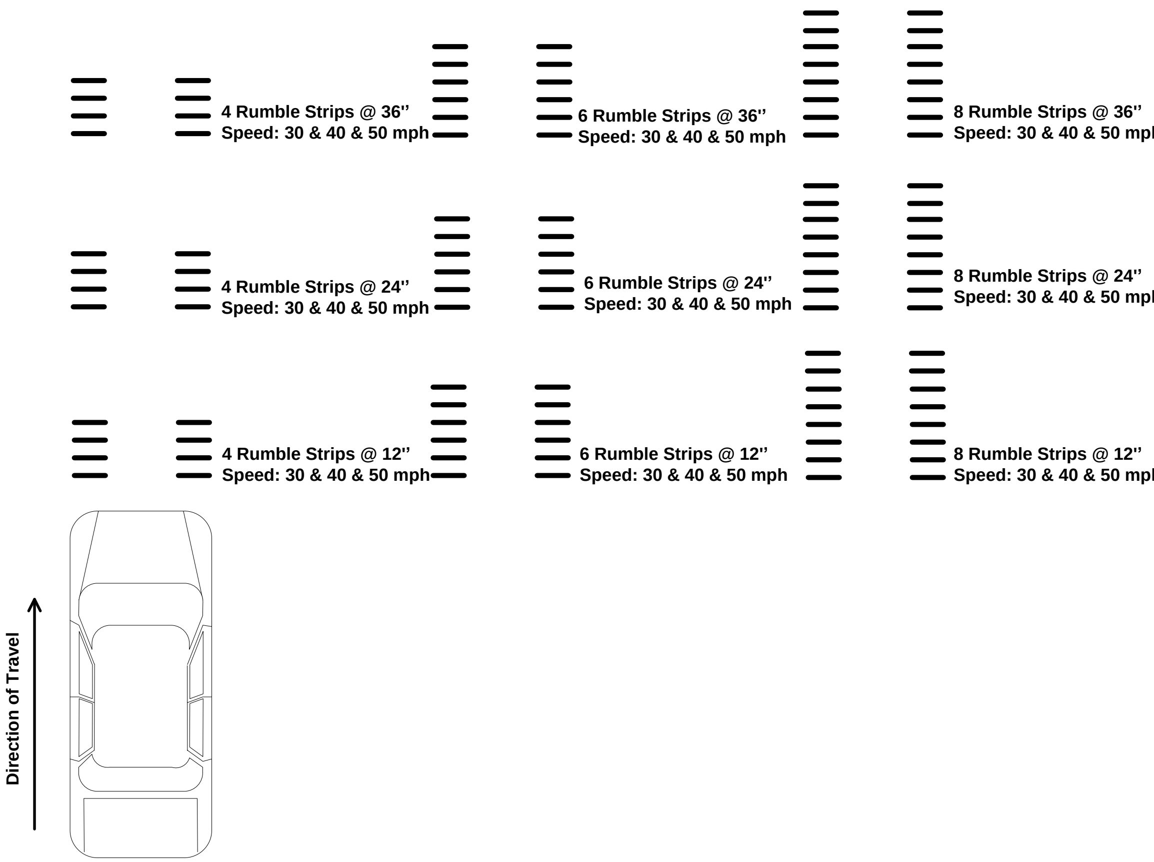


Figure 7.11 Temporary rumble strips patterns.

Figure 7.12 Temporary rumble strips alignment.

1- ATM Rumble Strips

Although ATM rumble strips were self adhesive, the manufacturer recommended the application of a thin layer of primer before attaching the strips to achieve better adhesion. The protective cover was then peeled from the adhesive on the back of strips and they were placed on the aligned road surface, as shown in Figure 7.13. No strips were directly applied on seams, joints, or deteriorating markings. The final step was to firmly tamp strips in the same direction of application. All strips were checked to insure that they have been completely conformed to road surface and all edges were firmly adhered.

Figure 7.13 ATM rumble strips installation process.

2- Swarco Rumble Strips

The first step to install the Swarco rumble strips was the application of one coat of Swarco contact cement RSCC-2 to the pre-aligned area of the road surface which was left for 15 minutes to dry until it was slightly tacky to the touch. Meanwhile, one coat of contact cement was applied to the back of the rumble strips and again it was left to dry until it was tacky to the touch. Second, a third coat of contact cement was applied to the pre-aligned area over the first coat and left to dry in a similar procedure to the first coat (see Figure 7.14). Finally, the strips were placed on the pavement and firmly tamped following the manufacturer’s tamping instruction.

Figure 7.14 Swarco rumble strips installation process.

3- RoadQuake Rumble Strips

The installation procedure for the RoadQuake rumble strips followed the general cleaning and alignment procedures however no adhesives were used. This type of temporary rumble strips does not need fasteners or adhesives for the installation as it is stable under its own weight (each strips weighs 105 lbs.). A crew of two researchers was needed to deploy, place and remove the strips, as shown in Figure 7.15.

Figure 7.15 RoadQuake rumble strips installation process.

The summary of the installation times experienced by a crew of four researchers to install each of the tested types of temporary rumble strips is presented in Table 7.1. Two crew members focused on aligning each segment pattern while the other two crew members applied the contact adhesive and peeled the protective backing from the back of strips. Finally, each strip was placed on the pavement and pressed into place. It should be noted that all members of the research team did not have any prior experience in installing these temporary rumble strips; therefore, it is likely that an experienced crew could have performed the installation process in shorter times.

Table 7.1 Installation Time of Temporary Rumble Strips Patterns (Alignment and Placement)

Temporary Rumble Strips Type	Installation Time (minutes)			Remarks
	8 strips	6 strips	4 strips	
1- ATM	~45	35	27	This includes cutting the strips into 4 feet long sections and applying one single coat of adhesive.
2- SWARCO	~45	38	31	This includes applying three coats of adhesive.
3- RoadQuake	~25	22	20	No adhesives are needed and the strips were very close to the work zone

7.5.2 Removal process

The removal process was simple. A corner has to be pulled up using a utility knife, or similar tool. For removing ATM and SWARCO temporary rumble strips, the researchers used a long handle square point shovel, as shown in Figure 7.16. After approximately 3 days, all strips were easily removed intact in few minutes, as shown in Figure 7.17. Although the removed strips were intact, the manufacturers of ATM and SWARCO do not recommend reusing the strips as the second use will require further coats of adhesive. On the other hand, the third tested type, RoadQuake, needs no adhesive and is designed for multiple uses. It should be noted that no strips were detached or displaced from the pavement during the experiments.

Figure 7.16 Removal of temporary rumble strips using square shovel.

Figure 7.17 Removal of temporary rumble strips after 3 days.

CHAPTER 8

EVALUATING THE EFFECTIVENESS OF TEMPORARY RUMBLE STRIPS

8.1 INTRODUCTION

This chapter presents the results of field experiments that were conducted to study and evaluate effectiveness of three temporary rumble strips in construction zones. A total of 27 different temporary rumble strips arrangements were tested in June 2009 at the Illinois Center for Transportation (ICT) in the University of Illinois at Urbana-Champaign. The description of the experiments setup, site preparation, rumble strips types, and testing vehicles were discussed in Chapter 6. This Chapter presents (1) the utilized data acquisition procedure during the field experiments; (2) the required sound levels to alert inattentive drivers; (3) an evaluation of the effectiveness of temporary rumble strips that are placed prior to work zones to generate auditory stimulus to alert motorists of the approaching work area and prompt them to reduce their speed; and (4) an evaluation of the effectiveness of temporary rumble strips that are placed at the edge of work zones to alert inattentive drivers if they encroach into the work area in a similar way that the permanent rumble strips are used to alert drivers when they drift off the road.

8.2 DATA ACQUISITION PROCEDURE

A sound level meter was used to measure the sound levels inside the cabin of the utilized vehicles. Sound level meters measure sound pressure levels and are commonly used in quantifying any noise out of specific industrial or environmental activity. The current international standard for sound level meter performance is IEC

61672:2003 that mandates the inclusion of an A-frequency-weighting filter. The DT-8851 Industrial High Accuracy Digital Sound Noise Level Meter was chosen for this study. The meter had a range of 30~130 decibels (dB) with an accuracy of ±1.4dB and had both A & C frequency weighting. The sound level meter was adjusted to record sound levels per 125mS (i.e.8 readings/second). The meter was attached inside the vehicle in the middle with the microphone sensor placed at the dashboard level. Figure 8.1 shows the position of the sound level meter inside the cabin of the sedan, and Figure 8.2 shows the location of the sound level meter inside the cabin of the cargo van. Only one data collection operator and a driver existed in each of the testing vehicles during each test.

Figure 8.1 Sound measuring equipment in the tested sedan

Figure 8.2 Sound measuring equipment in the tested cargo van

Sound levels were recorded inside the cabin of the three testing vehicles with the vehicle's fan and radio off, all of the windows closed, only one passenger and driver, and under dry, daytime conditions. The utilized procedure for measuring the auditory stimulus followed four steps: (1) field calibration of the sound level meter; (2) measuring sound levels without rumble strips; (3) identifying study parameters; and (4) measuring sound levels with rumble strips. The four steps will be discussed in more details in the following sections.

8.2.1 Field Calibration of Sound Level Meter

The sound level meter was field calibrated by recording a total number of 1701 sound readings over a 350 ft. track through 30 runs at a constant speed of 30 mph using the sedan testing vehicle. Table 8.1 represents a summary of calibration results. The standard deviation of the collected sound measures was 0.53 dBA.

Table 8.1 Field Calibration Results

Route number	Number of readings	Average reading per route in dBA
1	61	66.24
2	54	65.41
3	63	65.42
4	56	65.69
5	55	65.46
6	55	65.57
7	55	66.47
8	54	65.18
9	57	64.99
10	58	64.65
11	59	64.58
12	54	65.19
13	58	65.04
14	56	65.30
15	58	64.66
16	54	65.21
17	58	64.87
18	56	64.51
19	57	65.11
20	57	64.49
21	59	64.89
22	55	64.49
23	56	65.25
24	54	64.49
25	61	64.59
26	57	64.55
27	58	64.52
28	56	64.49
29	56	64.44
30	54	64.53
Total Number of Readings:		1701
Average readings:		65.01
Variance:		0.28
Standard Deviation:		0.53

8.2.2 Sound Levels of Ambient Environment without Rumble Strips

After calibrating the sound level meter at 30 mph, sound data were collected for the ambient environment without rumble strips. The goal was to record sound levels associated with the three testing vehicles travelling at a specified speed along a designated way that had no rumble strips. This data will then be used to determine the increase in sound level that is produced by each of the tested rumble strips configurations. Table 8.2 shows the ambient sound levels associated with each testing vehicle at different speed levels. All sound levels were recorded with the vehicle's fan and radio off and all of the windows closed.

Table 8.2 Ambient Sound Levels of Testing Vehicles

Testing Vehicle	Ambient Sound Levels in dBA
Sedan_30mph	65.01
Sedan_40mph	68.24
Sedan_50mph	70.14
Cargo Van_30mph	60.58
Cargo Van_40mph	63.91
Cargo Van_50mph	67.98
26' Truck_30mph	64.25
26' Truck_40mph	67.98
26' Truck_50mph	69.27

8.2.3 Study Parameters

A comprehensive literature review of previous studies on both temporary and permanent rumble strips indicates that the factors that influence the auditory stimulus experienced by motorists can be classified using six main parameters: (1) pattern of rumble strips; (2) spacing of strips; (3) rumble strips type; (4) vehicle type; (5) speed; and (6) location of rumble strips. Table 8.3 represents the 6 parameters and their associated observations. A spread sheet was developed to facilitate the input of all field sound levels for these six parameters.

Table 8.3 Study Parameters

Study Parameter	Observations
1- Pattern represents the number of strips per set	4 = 4 strips/set
	6 = 6 strips/set
	8 = 8 strips/set
2- Spacing represents the clear spacing between strips in a set	12 = 12 inches
	24 = 24 inches
	36 = 36 inches
3- Rumble Strips Type represents the temporary rumble strips type	1 = ATM
	2 = Swarco
	3 = RoadQuake
4- Vehicle Type represents the type of the testing vehicle	1= Sedan
	2= Cargo van
	3 = 26' Truck
5- Vehicle Speed represents the speed of the testing vehicle	30 mph
	40 mph
	50 mph
6- Location of Rumble Strips represents whether the rumble strips are located at the edge of work zones only under the left or right side wheels of the vehicle or prior to work zones under all wheels	1 = Prior to work zones
	2 = Edge of work zones

8.2.4 Sound Levels of Installed Rumble Strips

Sound levels were collected continuously as the testing vehicles traversed different patterns of rumble strips. As a testing vehicle traversed a certain pattern of rumble strips, all sound readings were immediately logged into a laptop computer and saved for later analysis. Figure 8.3 shows a graphical sample of collected sound level frequencies depicting three peaks that represent the change of the sound level experienced in the cabin of a testing vehicle when traversing three different patterns of rumble strips. All numerical sound levels were recorded as notepad files depicting sound levels recorded at a rate of 125mS (i.e., 8 readings/second). The numerical data were then imported into a spread sheet for further analysis. Table 8.4 shows the sound level records of a cargo van traversing three sets of different patterns of rumble strips of type Swarco at a speed of 40 mph. From Table 8.4, three peaks can be identified at 78.6, 76.3, and 79.9 dBA which represent the effect of the three patterns of rumble strips on generating auditory stimulus experienced by motorists.

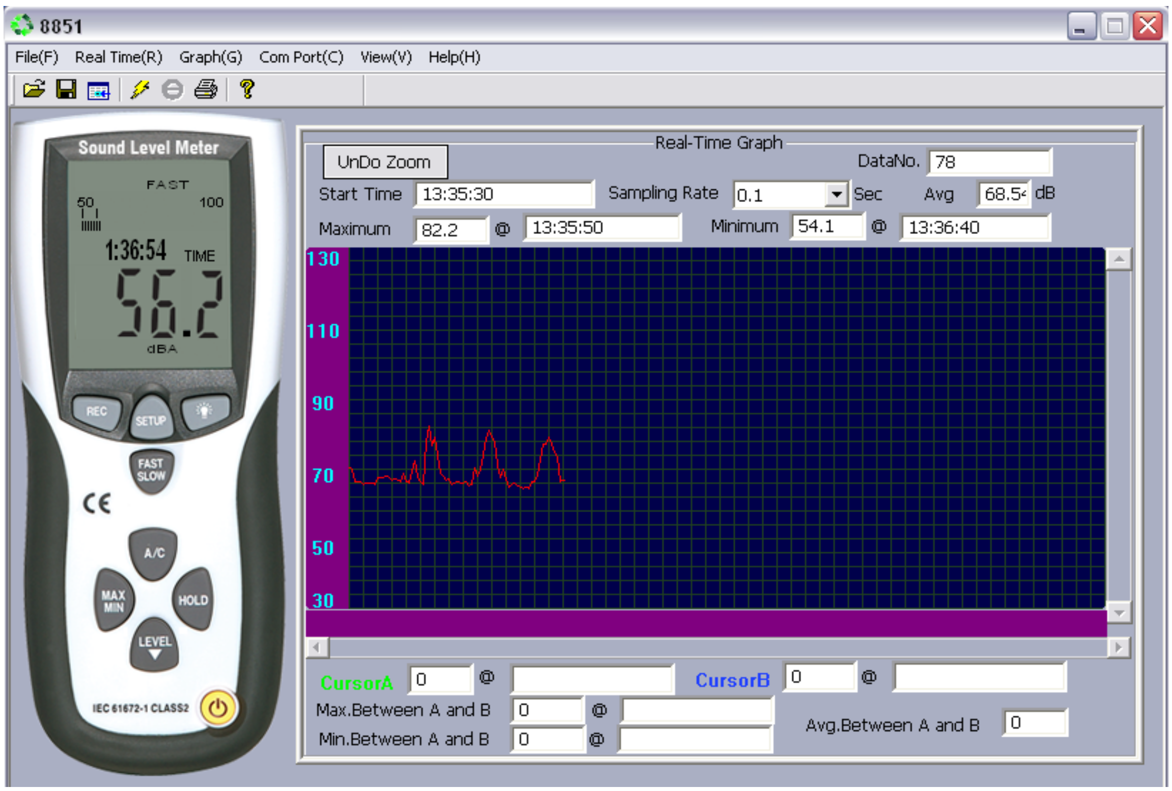


Figure 8.3 Sound level meter graphical user interface.

Table 8.4 Sound Level Records of a Cargo Van Traversing Three Different Sets of Temporary Rumble Strips

Date	Time	Reading	Unit
9/6/2009	17:55:46	63.3	dBA
9/6/2009	17:55:46	63.7	dBA
9/6/2009	17:55:46	63.4	dBA
9/6/2009	17:55:46	63.8	dBA
9/6/2009	17:55:47	63.4	dBA
9/6/2009	17:55:47	63.9	dBA
9/6/2009	17:55:47	64.4	dBA
9/6/2009	17:55:47	64.3	dBA
9/6/2009	17:55:47	68.1	dBA
9/6/2009	17:55:47	69.4	dBA
9/6/2009	17:55:47	75.9	dBA
9/6/2009	17:55:47	73.7	dBA
9/6/2009	17:55:48	78.6	dBA
9/6/2009	17:55:48	72.8	dBA
9/6/2009	17:55:48	68.5	dBA
9/6/2009	17:55:48	66.6	dBA
9/6/2009	17:55:48	65	dBA
9/6/2009	17:55:48	64.2	dBA
9/6/2009	17:55:48	63.8	dBA
9/6/2009	17:55:48	64	dBA
9/6/2009	17:55:49	64	dBA
9/6/2009	17:55:49	64.6	dBA
9/6/2009	17:55:49	69.6	dBA
9/6/2009	17:55:49	67.9	dBA
9/6/2009	17:55:49	68.7	dBA
9/6/2009	17:55:49	73.9	dBA
9/6/2009	17:55:49	75.6	dBA
9/6/2009	17:55:49	76.3	dBA
9/6/2009	17:55:50	74.6	dBA
9/6/2009	17:55:50	67.9	dBA
9/6/2009	17:55:50	65.4	dBA
9/6/2009	17:55:50	64.4	dBA
9/6/2009	17:55:50	64	dBA
9/6/2009	17:55:50	64.6	dBA
9/6/2009	17:55:50	65.5	dBA
9/6/2009	17:55:50	64.4	dBA
9/6/2009	17:55:51	64	dBA
9/6/2009	17:55:51	64.6	dBA
9/6/2009	17:55:51	64	dBA
9/6/2009	17:55:51	69.4	dBA
9/6/2009	17:55:51	75.8	dBA
9/6/2009	17:55:51	79.6	dBA
9/6/2009	17:55:51	79.9	dBA
9/6/2009	17:55:51	79.9	dBA
9/6/2009	17:55:52	71.6	dBA
9/6/2009	17:55:52	68.7	dBA
9/6/2009	17:55:52	65.5	dBA
9/6/2009	17:55:52	65.9	dBA
9/6/2009	17:55:52	65	dBA
9/6/2009	17:55:52	65.4	dBA
9/6/2009	17:55:52	65.4	dBA

A total of 351 sound level readings were collected and stored in the spreadsheet that represent different configurations of study parameters and rumble strips. A segment of the spread sheet is presented in Table 8.5 that illustrates the effect of rumble strips which was calculated as the difference between the sound level inside the test vehicle on a road with and without rumble strips. Sound readings of all tested patterns of rumble strips are presented in Appendix E.

Table 8.5 Sample of the Sound Data Acquisition Spread Sheet

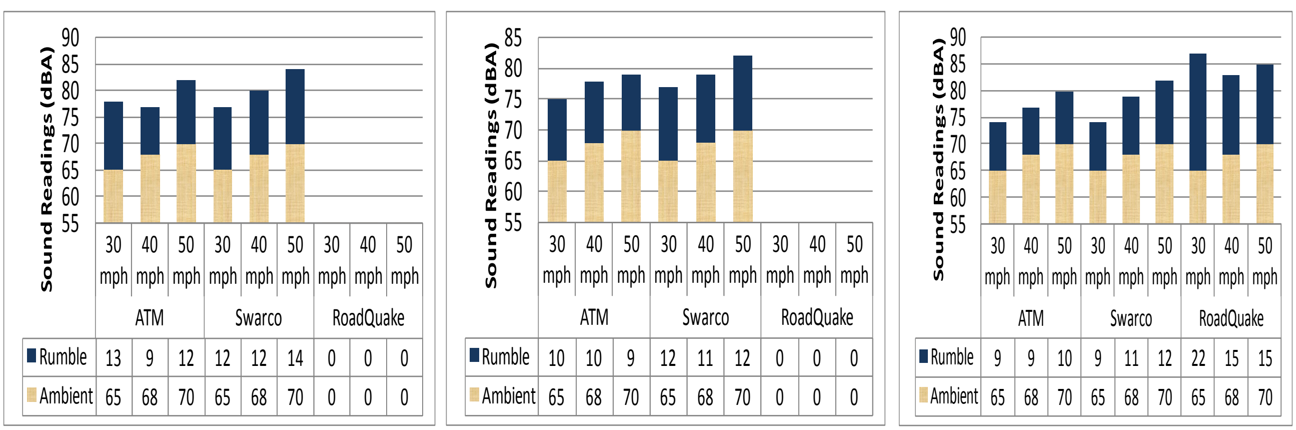
Reading No.	Pattern	Vehicle Type	Rumble Strips Type	Speed	Spacing	Sound Readings		
						Ambient Environment	Traversing Rumble Strips	Rumble Strips Effect (dBA)
1	8strips/set	Sedan	ATM	50	12	70.14	80.4	10.26
2					24	70.14	84.3	14.16
3					36	70.14	80.5	10.36
4				40	12	68.24	80.7	12.46
5					24	68.24	80	11.76
6					36	68.24	77.3	9.06
7				30	12	65.01	78.6	13.59
8					24	65.01	77.3	12.29
9					36	65.01	74.5	9.49
10			Swarco	50	12	70.14	84.9	14.76
11					24	70.14	84.4	14.26
12					36	70.14	83.3	13.16
13				40	12	68.24	80.3	12.06
14					24	68.24	80.8	12.56
15					36	68.24	82.7	14.46
16				30	12	65.01	78.5	13.49
17					24	65.01	77.2	12.19
18					36	65.01	77.2	12.19
19			Road Quake	50	36	70.14	83.5	13.36
20				40	36	68.24	82.7	14.46
21				30	36	65.01	87.7	22.69

8.3 ADEQUATE SOUND LEVELS TO ALERT DRIVERS

Kinetic energy represented in sound and vibration is the direct outcome of tire displacement over temporary rumble strips. Whenever tire displacement increases, more energy is converted which results in more sound and vibration. Consequently, rumble strips design characteristics such as width, height, and spacing have direct influence on the generated sound and vibration. For example, increasing the height of rumble strips increased the generated sound recorded for certain limits. Other factors describing vehicles characteristics such as vehicle type, vehicle speed, and number of tire traversing rumble strips affect the generated sound as well. In order to quantify the auditory stimulus experienced by motorists, sound data records were measured for 351 test patterns as described earlier. In order to decide if a change in sound levels due to temporary rumble strips is loud enough to alert motorist, it is important to analyze existing literature on this topic which is summarized in the following paragraphs.

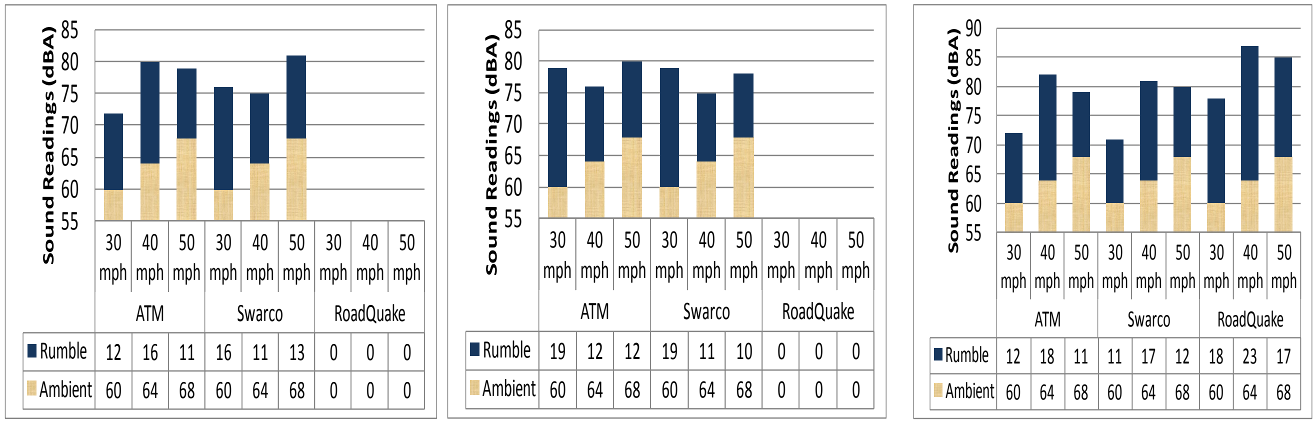
A previous study performed by Higgins and Barbel (1984) compared various configurations of different types of permanent rumble strips and reported an average sound level change of 7 dB over regular noise levels produced by traffic on normal pavement. Elefteriadoiu et al. (2000) studied sound level changes inside the cabin of a passenger minivan traversing various types of permanent rumble strips at various speeds and reported a sound level change of 12 dB. In a more recent study by Miles and Finley (2007), the researchers considered increases of 4 dB or greater to be sufficient to alert motorists when traversing temporary rumble strips. Accordingly, a sound level change that ranges from 4 to 12 dB can be considered adequate to alert motorists of the upcoming work zone. Since vibration was significantly correlated with generated sound, an upper limit of sound level change of 20 dB can be imposed to limit the risks of excessive vibration experienced by vehicles traversing temporary rumble strips. It should be noted that there is no reported research that specifies the required thresholds of vibration needed to alert motorists (Finley and Miles 2006). Accordingly, the analysis in this study focused on measuring and evaluating the generated sound level changes due to utilizing various configurations of temporary rumble strips.

Sound levels measured during the various test configurations with and without the use of temporary rumble strips are compared to illustrate the sound level changes that were generated as a result of utilizing these strips. As shown in Figures 8.4, 8.5 and 8.6, the ambient sound level (without the use of temporary rumble strips) inside the three testing vehicles increased with the increase in speed limit. The cargo van had the lowest ambient sound levels when compared with the sedan and the 26foot truck, regardless of the speed limit. However, the van generally experienced a higher increase in sound levels when it traversed rumble strips than the sedan. The truck generated ambient sound levels slightly less than the sedan; however, the increase of sound levels of traversed rumble strips varies depending on vehicle's speed, types, and spacings of the rumble strips. As shown in Figure 8.6, the highest sound level recorded was 92 dBA and it was recorded for a truck crossing a set of RoadQuake rumble strips at 30 mph. The effect of study parameters on increasing sound levels inside the cabin of vehicles will be discussed in details in the next chapter.



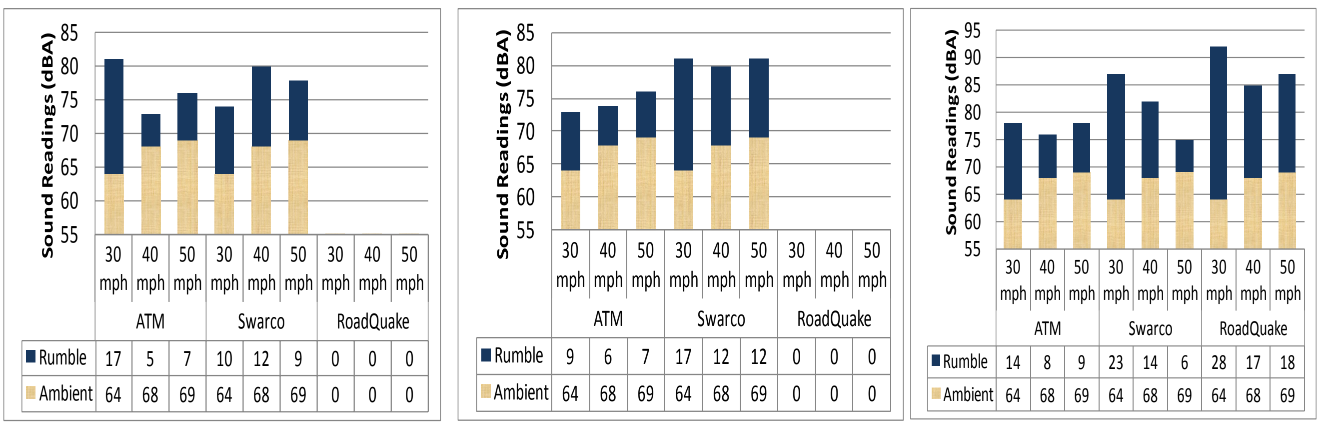
(a) (b) (c)

Figure 8.4 Change in sound level inside a sedan traversing 6 strips of rumble strips spaced at: (a) 12"; (b) 24"; and (c) 36".



(a) **(b)** **(c)**

Figure 8.5 Change in sound level inside a van traversing 6 strips of rumble strips spaced at: (a) 12”; (b) 24”; and (c) 36”.



(a) **(b)** **(c)**

Figure 8.6 Change in sound level inside a 26-foot truck traversing 6 strips of rumble strips spaced at: (a) 12”; (b) 24”; and (c) 36”.

8.4 EVALUATING THE EFFECTIVENESS OF TEMPORARY RUMBLE STRIPS PRIOR TO WORK ZONES

This section presents the results of the field experiments that were conducted to evaluate the effectiveness of temporary rumble strips that are placed prior to the work zones to generate auditory stimulus to alert motorists of the approaching work area and prompt them to reduce their speed. The impact of the aforementioned six main rumble strips and vehicle parameters (see Table 8.3) on the generated sound level were studied in order to identify recommendations to improve the design and layout of temporary rumble strips around work zones. All combinations of these six analyzed parameters were tested to evaluate the effectiveness of: (1) three rumble strips patterns; (2) three rumble strips spacing arrangements; (3) three rumble strips types; (4) three vehicle types; (5) three vehicle speeds; and (6) two locations of rumble strips, as shown in Table 6.3. While the first five parameters were varied, the sixth parameter (i.e., location of rumble strips) was fixed and selected to be prior to work zones under all wheels of the test vehicles for all the tested configurations in this section. This set up for the sixth parameter represents a typical location of rumble strips prior to work zones to alert drivers of nearby construction work. The results of the conducted tests for the second location of rumble strips at the edge of the work zone (i.e., under the wheels of only one side of the vehicle) will be discussed in section 8.5 of this chapter.

8.4.1 Correlation Analysis of Study Parameters and Change in Sound Levels

A correlation analysis was used in this study to identify potential correlations between the measured sound level changes that represent the effectiveness of the temporary rumble strips and the other analyzed study parameters listed in Table 8.3. Two statistical tests for independence were used in this study to test all possible correlations among the study parameters: Pearson chi-square, and likelihood-ratio chi-square (Bai and Li 2006, SAS Institute Inc. 2006). The p-values for both statistical tests were calculated to test whether a null hypothesis could be accepted or not, and for a particular level of significance such as 5%, if p-value is larger than or equal to 0.05, the null hypothesis H_0 will be considered and the study parameter and sound level are not correlated. If the p-value is less than 0.05, the alternative hypothesis H_1 will be considered and a correlation exists. The two statistical tests were performed for identifying all possible correlations and a dependent relationship was determined if both tests supported it (i.e., p-value < 0.05). As shown in Table 8.6, the findings of this correlation analysis indicate that the "sound level readings" variable is correlated with four study parameters: (1) spacing of rumble strips; (2) type of rumble strips; (3) type of vehicle; and (4) vehicle speed. This indicates that these variables need to be carefully considered and analyzed during the design of temporary rumble strips that are placed prior to work zones under all the wheels of vehicles approaching work zones. A detailed analysis of these four parameters is presented in the following section.

Table 8.6 Correlated Parameters of Rumble Strips Auditory

Correlated Factors of Rumble Strips Auditory Stimulus		**Pearson Chi-Square**		**Likelihood Ratio Chi-Square**	
		P-Value	**Related**	**P-Value**	**Related**
Sound measurement	Number of strips per set	0.1556	NO	0.1442	NO
Sound measurement	Rumble strips spacing	<0.0001	YES	<0.0001	YES
Sound measurement	Rumble strips type	<0.0001	YES	<0.0001	YES
Sound measurement	Vehicles type	<0.0001	YES	<0.0001	YES
Sound measurement	Vehicles speed	0.0038	YES	0.0022	YES

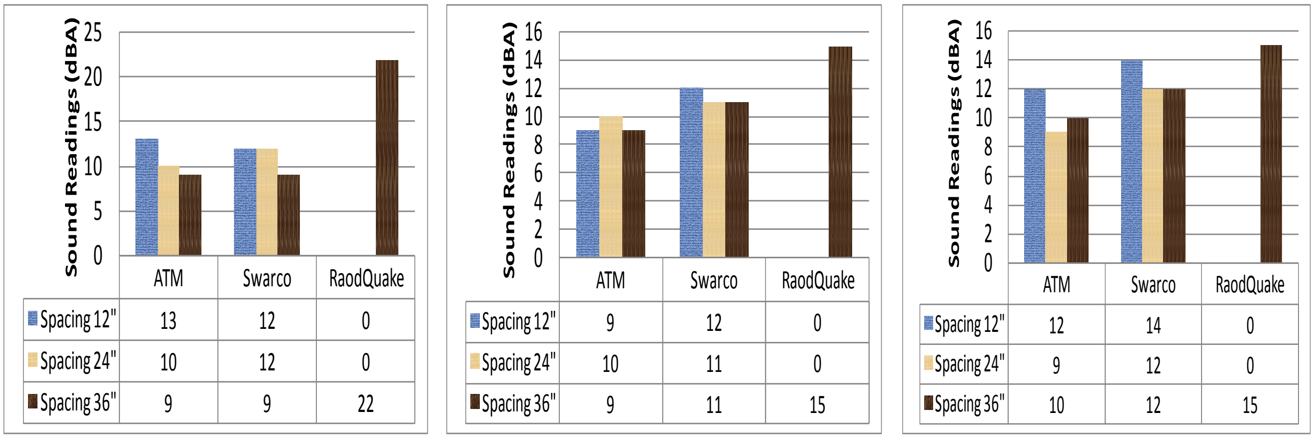
The next sections present an in depth analysis of the four study parameters that were found to be correlated with the measured sound level changes during the experiments: (1) spacing between rumble strips; (2) rumble strips type; (3) vehicle speed; and (4) vehicle type.

8.4.2 Impact of Rumble Strips Spacing

The spacing between rumble strips was found to be statistically correlated with the increase in sound level due to the utilization of temporary rumble strips as shown in

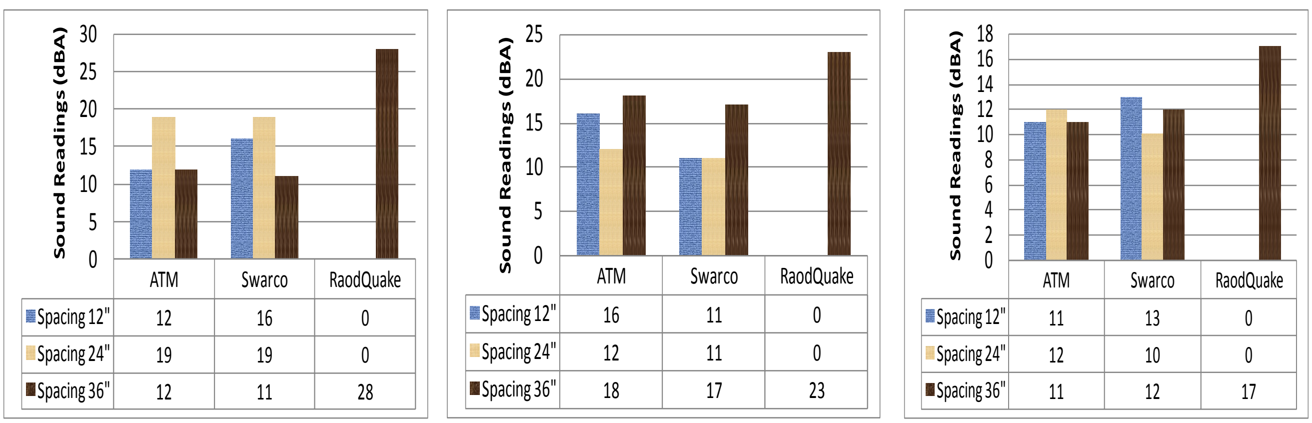
Table 8.6. The goal of the detailed spacing analysis is to evaluate the impact of varying the spacing of temporary rumble strips on its effectiveness that can be measured by the change in sound levels. Based on previous literature and manufactures recommendation, three spacing observations were considered in the field experiments: 12 inches, 24 inches, and 36 inches. Two types of rumble strips, ATM and Swarco, were tested using three configurations that utilized these three different spacing arrangements. The third type, RoadQuake, was tested only using a 36 inches spacing arrangements because of its significantly larger dimensions and heavier weight than the other two types of tested rumble strips. Since the patterns of rumble strips (the number of strips per set) was not found to be statistically correlated with the increase in sound levels, only one pattern of 6 strips per set of different configurations is presented in Figures 8.7, 8.8, and 8.9. The records of other tested rumble strips patterns (4 and 8 strips per set) are listed in Appendix F.

As shown in Figure 8.7, the sound level changes inside the sedan ranged between 9 dBA and 22 dBA and it generally decreased as the spacing of rumble strips increased. The lowest sound level change (9 dBA) was recorded for ATM rumble strips at different spacing arrangements and vehicle speeds. The largest sound level change (22 dBA) was recorded for the RoadQuake rumble strips at a spacing of 36 inches and a speed of 30 mph. As shown in Figure 8.8 and Figure 8.9, the previous trend changed for the van and the truck as the larger spacing arrangements of 24 inches and 36 inches generated higher sound level changes than the spacing of 12 inches. The lowest sound level change (5 dBA) was recorded for the truck traversing the ATM rumble strips that had a spacing of 12 inches. The sound level change was at or above 9 dBA for all vehicles, speeds, and spacing arrangements with the exception of the ATM spacing arrangements of 12 inches and 24 inches for the 26-foot truck when it travelled at speeds higher than 30 mph.



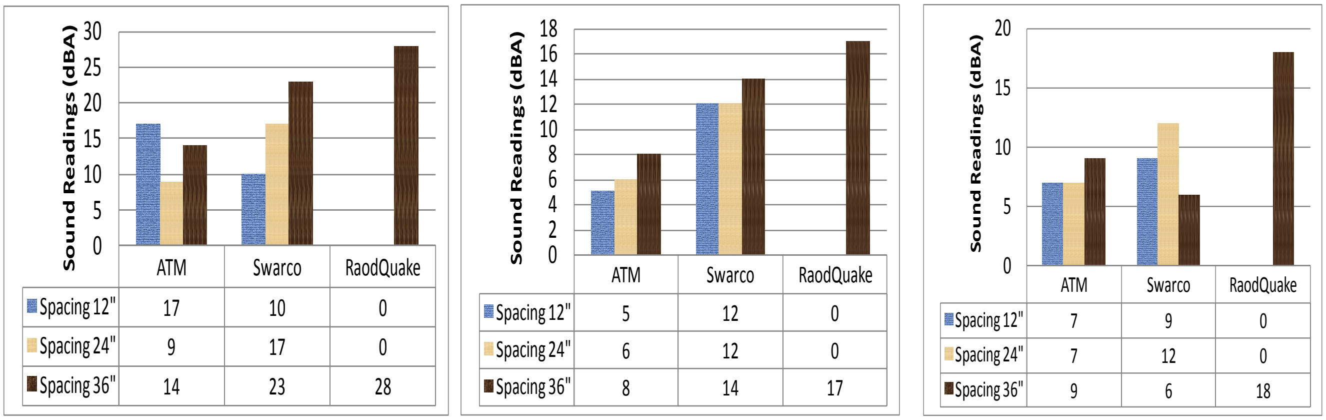
(a) **(b)** **(c)**

Figure 8.7 Change in sound level inside a sedan traversing 6 strips of rumble strips at: (a) 30 mph; (b) 40 mph; and (c) 50 mph.



(a) **(b)** **(c)**

Figure 8.8 Change in sound level inside a van traversing 6 strips of rumble strips at: (a) 30 mph; (b) 40 mph; and (c) 50 mph.



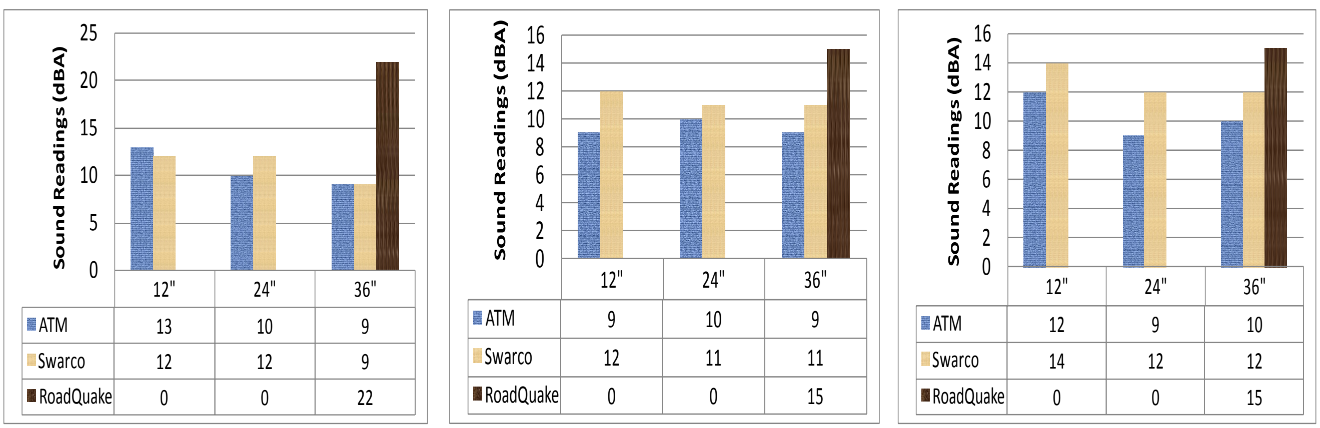
(a) **(b)** **(c)**

Figure 8.9 Change in sound level inside a 26 ft truck traversing 6 strips of rumble strips at: (a) 30 mph; (b) 40 mph; and (c) 50 mph.

8.4.3 Impact of Rumble Strips Type

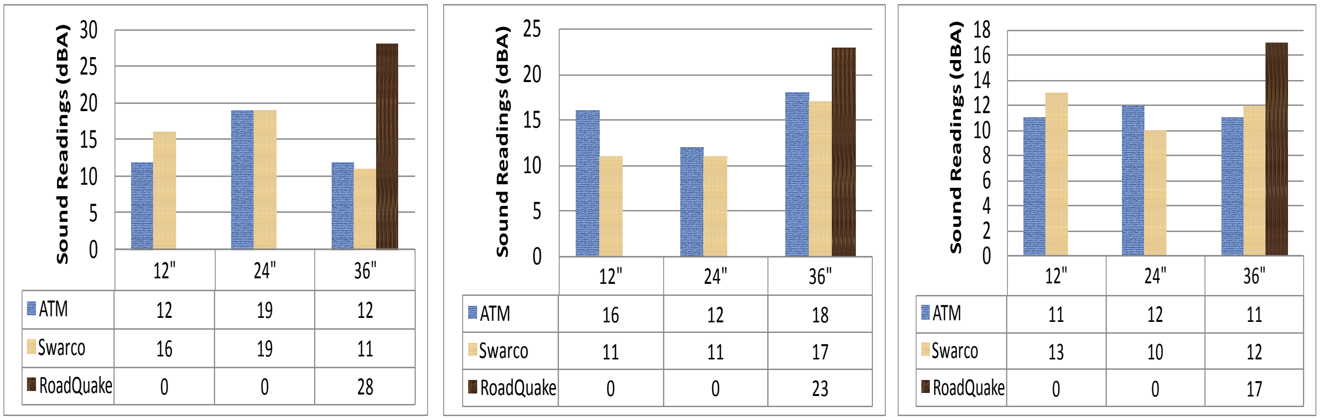
The type of rumble strips was found to be statistically correlated with the increase in the measured sound level during the experiments as shown in Table 8.6. This detailed analysis is performed to evaluate the impact of the type of temporary rumble strips on its effectiveness. Based on a review of commonly used types of temporary rumble strips in and around work zones and consultations with IDOT officials, three temporary rumble strips were tested in the field experiments: ATM, Swarco, and RoadQuake. The ATM and Swarco types were tested using three configurations that used spacing arrangements of 12, 24, and 36 inches while the RoadQuake type was tested using only a spacing of 36 inches due to its larger dimensions. Figures 8.10, 8.11, and 8.12 illustrate the impact of rumble strips type on the generated sound levels for the tested arrangements of 6 strips per set of different configurations. The records of other tested rumble strips patterns (4 and 8 strips per set) are listed in Appendix F.

This analysis indicates that the RoadQuake rumble strips generated higher sound level changes inside all the tested vehicles than the Swarco and ATM rumble strips, as shown in Figures 8.10, 8.11, and 8.12. The Swarco rumble strips generated higher sound levels than ATM rumble strips except for the 26-foot truck travelling at speeds below 40 mph. For the tested sedan, the recorded sound level changes ranged from 9 dBA to 22 dBA with the largest sound change (22 dBA) encountered during the testing of the RoadQuake strips at a spacing of 36 inches and a speed 30 mph, as shown in Figure 8.10. The RoadQuake rumble strips at a spacing of 36 inches also produced the largest sound change (28 dBA) for the 26-foot truck traveling at a speed of 30 mph, as shown in Figure 8.12. The results also indicate that the sound level changes were at or above 9 dBA for all vehicles, speeds, and spacing arrangements with the exception of the ATM rumble strips when it was tested using the 26-foot truck at spacing arrangements of 12 inches and 24 inches and speeds higher than 30 mph.



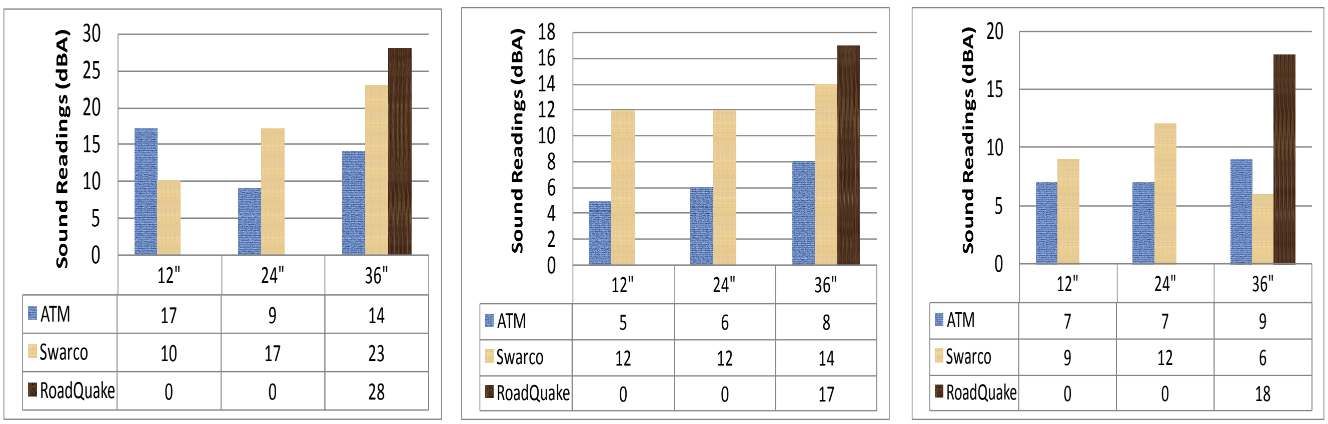
(a) **(b)** **(c)**

Figure 8.10 Change in sound level inside a sedan traversing 6 strips of rumble strips at: (a) 30 mph; (b) 40 mph; and (c) 50 mph.



(a) **(b)** **(c)**

Figure 8.11 Change in sound level inside a van traversing 6 strips of rumble strips at: (a) 30 mph; (b) 40 mph; and (c) 50 mph.



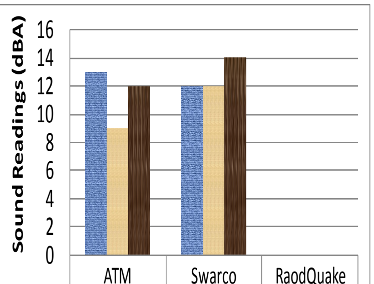
(a) **(b)** **(c)**

Figure 8.12 Change in sound level inside a truck traversing 6 strips of rumble strips at: (a) 30 mph; (b) 40 mph; and (c) 50 mph.

8.4.4 Impact of Vehicle Speed

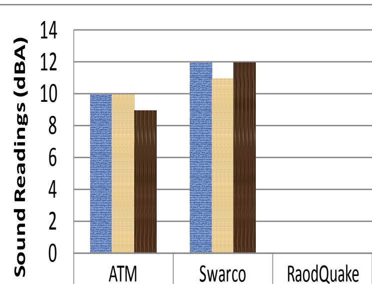
There are many parameters with respect to vehicle characteristics that can affect the generated sound levels when crossing over rumble strips, including vehicle speed, vehicle type, and tire specifications (Caltrans 2001, Morgan 2003, Miles and Finley 2007). This section provides a detailed analysis of the impact of the vehicle speed on the generated sound level changes. During the experiments, the test vehicles were driven at 30, 40, and 50 mph along all the tested patterns of rumble strips. These speed values were selected to be consistent with the typical speed limits used around work zones in the State of Illinois. Figures 8.13, 8.14 and 8.15 illustrate the impact of vehicle speed on the generated sound levels for the tested arrangements of 6 strips per set of different configurations. The records of other tested rumble strips patterns (4 and 8 strips per set) are listed in Appendix F.

As shown in Figures 8.13 through 8.15, a vehicle speed of 30 mph generally generated higher sound levels than the speeds of 40 and 50 mph. The van however generated higher sound levels at 40 mph when it travelled across rumble strips that are spaced at 36 inches as shown in Figure 8.14. The results also show that the sedan and the van generated sound levels that ranged between 9 and 23 dBA, as shown in Figures 8.13 and 8.14 while the 26-foot truck generated sound levels that ranged between 7 and 28 dBA, as shown in Figure 8.15.



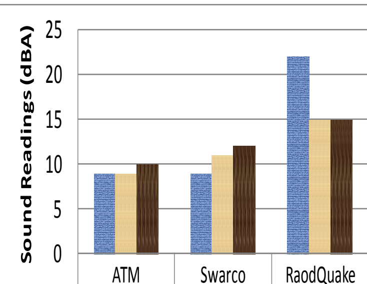
	ATM	Swarco	RaodQuake
Speed 30 mph	13	12	0
Speed 40 mph	9	12	0
Speed 50 mph	12	14	0

(a)



	ATM	Swarco	RaodQuake
Speed 30 mph	10	12	0
Speed 40 mph	10	11	0
Speed 50 mph	9	12	0

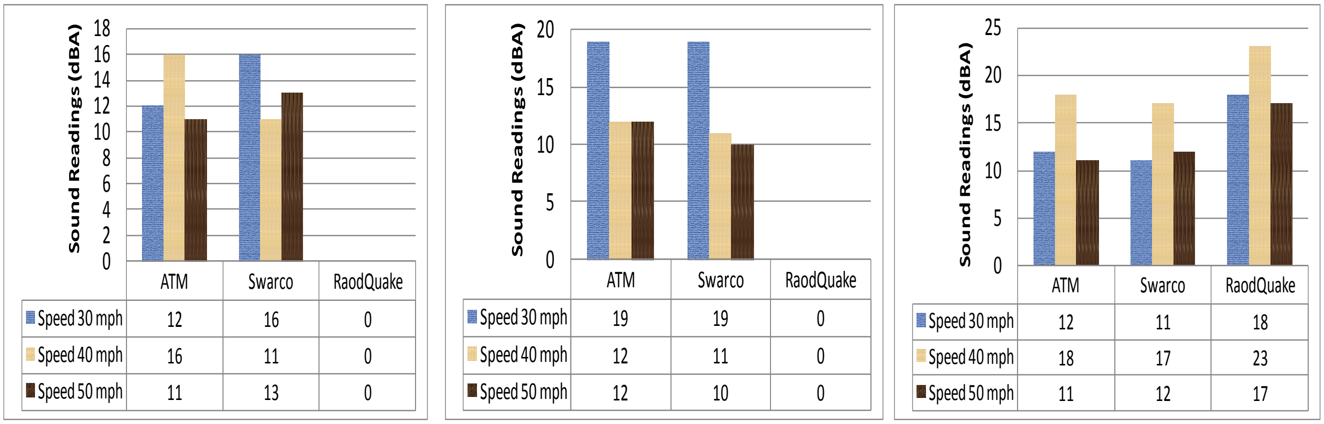
(b)



	ATM	Swarco	RaodQuake
Speed 30 mph	9	9	22
Speed 40 mph	9	11	15
Speed 50 mph	10	12	15

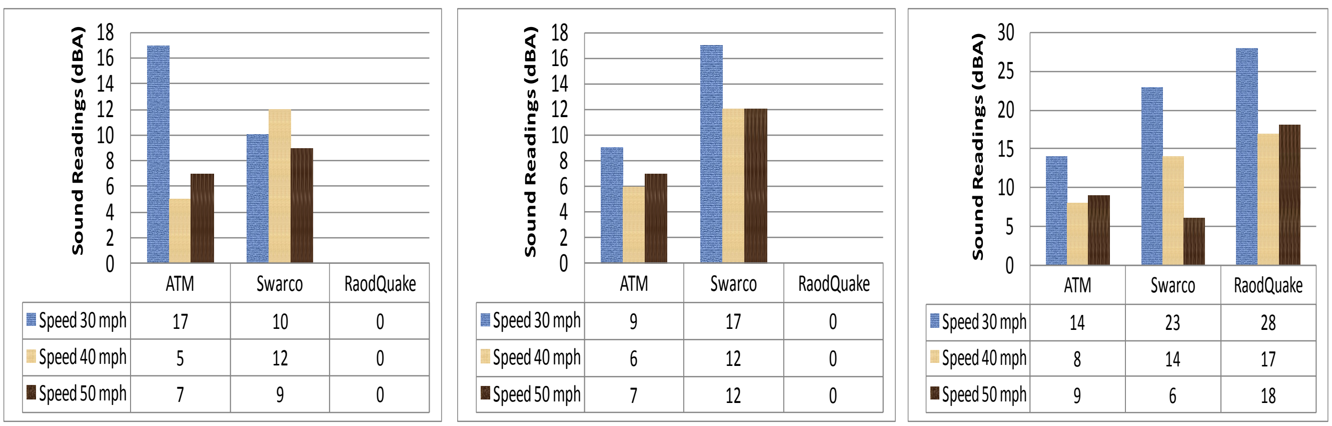
(c)

Figure 8.13 Change in sound level inside a sedan traversing 6 strips of rumble strips spaced at: (a) 12”; (b) 24”; and (c) 36”.



(a) **(b)** **(c)**

Figure 8.14 Change in sound level inside a van traversing 6 strips of rumble strips spaced at: (a) 12”; (b) 24”; and (c) 36”.

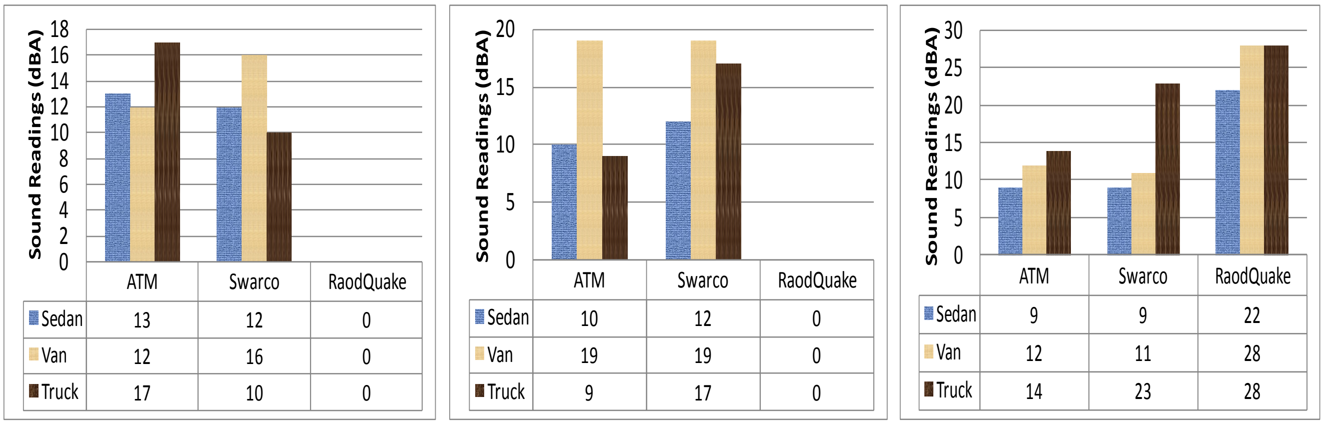


(a) **(b)** **(c)**

Figure 8.15 Change in sound level inside a 26-foot truck traversing 6 strips of rumble strips spaced at: (a) 12”; (b) 24”; and (c) 36”.

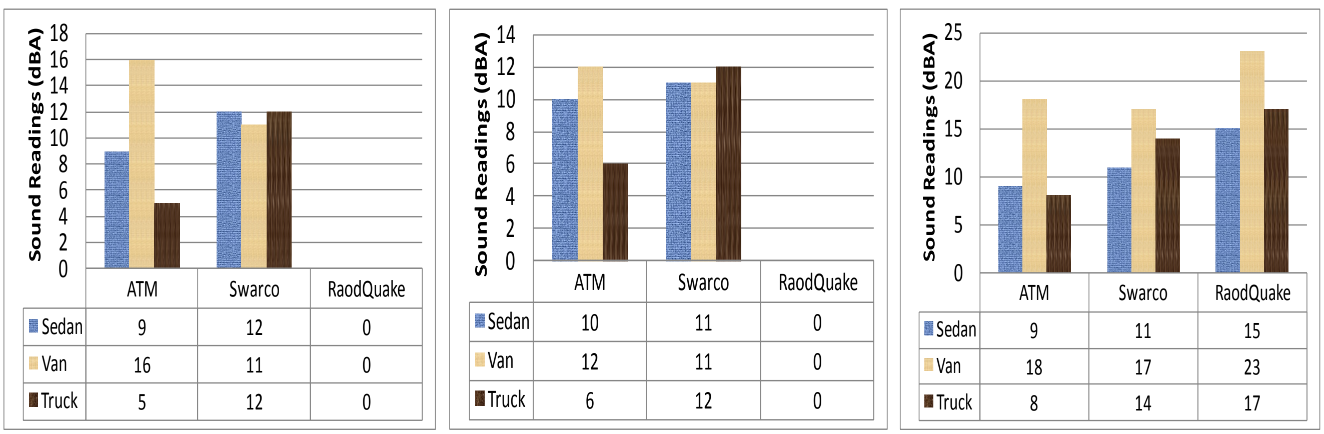
8.4.5 Impact of Vehicle Type

This section provides a detailed analysis of the impact of the vehicle type on the generated sound level changes. Three different vehicles were used in the field experiments to measure the sound level changes inside these vehicles when they travelled over various configurations and set ups of temporary rumble strips. Figures 8.16, 8.17 and 8.18 illustrate the impact of vehicle type on the generated sound levels for the tested arrangements of 6 strips per set of different configurations. The results of other tested rumble strips patterns (4 and 8 strips per set) are listed in Appendix F. The results of this analysis indicate that the van generally generated sound level changes higher than the sedan, as shown in Figures 8.16 through Figure 8.18.



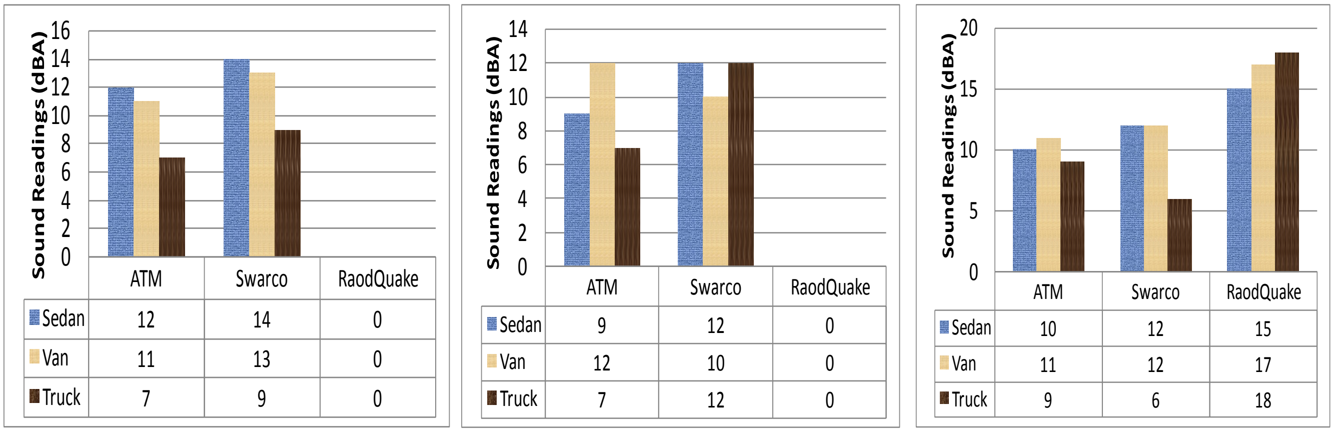
(a) **(b)** **(c)**

Figure 8.16 Change in sound level inside different testing vehicles traversing at 30 mph 6 strips of rumble strips spaced at: (a) 12”; (b) 24”; and (c) 36”.



(a) **(b)** **(c)**

Figure 8.17 Change in sound level inside different testing vehicles traversing at 40 mph 6 strips of rumble strips spaced at: (a) 12”; (b) 24”; and (c) 36”.



(a) **(b)** **(c)**

Figure 8.18 Change in sound level inside different testing vehicles traversing at 50 mph 6 strips of rumble strips spaced at: (a) 12”; (b) 24”; and (c) 36”.

8.4.6 Summary

Section 8.2 focused on evaluating the effectiveness of temporary rumble strips prior to work zones in order to enhance the alertness of drivers approaching the work area. In order to achieve this objective, a series of field experiments were performed in June 2009 to evaluate the performance of three widely used types of temporary rumble strips: (1) ATM of Advance Traffic Markings; (2) RoadQuake of Plastic System Safety; and (3) Rumbler of Swarco Industries Inc. The three different types of temporary rumble strips have been tested using three vehicles: a sedan; a cargo van; and a 26-ft truck.

The effectiveness of temporary rumble strips was quantified by measuring the generated sound levels of traversing vehicles over temporary rumble strips in order to evaluate the impact of five rumble strips and vehicle parameters: (a) rumble strips type; (b) number of rumble strips per set; (c) rumble strips spacing; (d) vehicle type; and (e) vehicle speed. A correlation analysis was performed to identify all possible correlations among these study parameters and the increase in generated sound level. The increase in sound level was found to be statistically correlated with all study parameters except the number of rumble strips per set.

The increase in sound level due to the utilization of temporary rumble strips prior to work zones ranged between 5 dBA and 28 dBA for all the tested rumble strips configurations and vehicle speeds. Sound level changes were found to be at or above 9 dBA for all vehicles, speeds, and spacing arrangements with the exception of the ATM rumble strips that had a spacing of 12 and 24 inches when traversed by the 26-foot truck at speeds higher than 30 mph. The RoadQuake rumble strips generated higher sound levels than the Swarco and ATM rumble strips. The speed limit of 30 mph generally generated higher sound level changes than the speeds 40 and 50 mph.

8.5 EVALUATING THE EFFECTIVENESS OF TEMPORARY RUMBLE STRIPS AT THE EDGE OF WORK ZONES

This section presents the results of the field experiments that were conducted to evaluate the effectiveness of temporary rumble strips placed at the edge of work zones. This location of temporary rumble strips can be used to alert inattentive drivers if they encroach into the work area in a similar way that the permanent rumble strips are used to alert drivers when they drift off the road. The location of temporary rumble strips at the edge of work zones requires that their length range between 2 and 4 feet, as shown in Figure 8.19. This new approach of deploying temporary rumble strips of small lengths (2~4 feet) has the potential to be applied along construction work zones and significantly decrease the percentage of work zone crashes especially at the work area.

The installation and removal process of temporary rumble strips have been presented in details in the previous chapter in addition to the efficiency of the different tested types in terms of the time and effort required for both the installation and removal process. The field experiments on temporary rumble strips at the edge of work zones tested two types of rumble strips: (1) ATM of Advance Traffic Markings; and (2) Rumbler of Swarco Industries Inc. The first type, ATM, is available in rolls of 50 feet that are cut into smaller strips of any desirable length. The second type, Swarco, is available in strips with 4 feet in length. The third type, RoadQuake, is only available in strips of 11 feet long that cover the entire traffic lane. Therefore, the RoadQuake rumble strips was not tested as a potential type for utilization at the edge of work zones. The two types of temporary rumble strips were tested using three vehicles: (1) sedan; (2) cargo van; and (3) 26-ft truck. Full specifications of the testing vehicles are presented in Chapter 6.

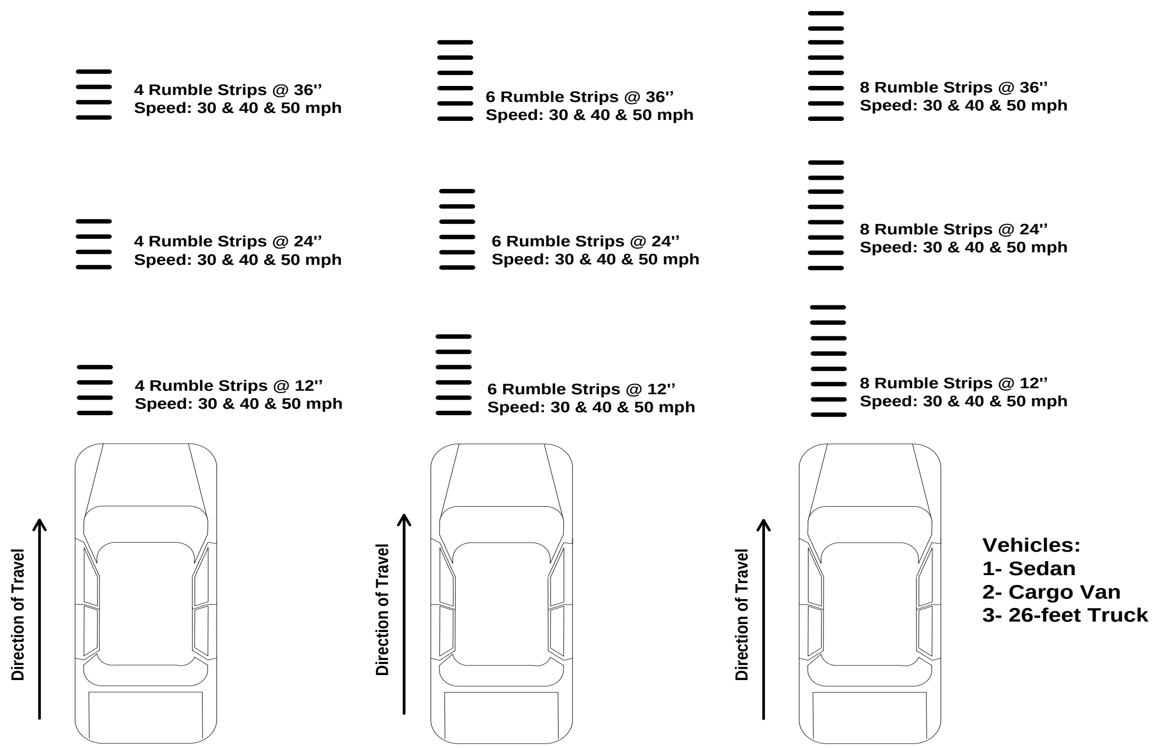


Figure 8.19 Tested patterns temporary rumble strips at the edge of work zones

The effectiveness of temporary rumble strips at the edge of work zones was quantified by measuring the generated sound levels of traversing vehicles over temporary rumble strips for 5 parameters: (1) number of rumble strips per set; (2) rumble strips spacing; (3) rumble strips type; (4) vehicle speed; and (5) vehicle type. A total number of 162 temporary rumble strips configurations were tested. The same procedure of data collection of sound readings described in Chapter 7 was utilized in these experiments.

8.5.1 Comparing the Effectiveness of Temporary and Permanent Rumble Strips

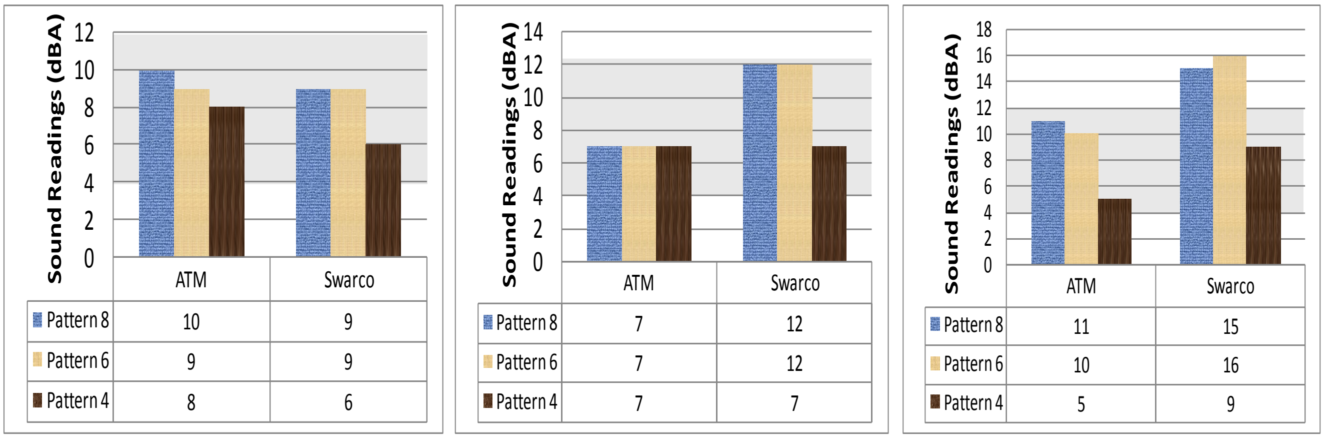
The effectiveness of temporary rumble strips at the edge of work zones was first evaluated by comparing the generated sound levels to those produced by permanent rumble strips that are typically placed at the edge of roads. Various research studies have measured and reported the generated sound levels of typical permanent rumble strips inside the cabin of vehicles, as shown in Table 8.7. The findings of these research studies indicate that typical permanent rumble strips generate an increase in sound levels inside the vehicle that ranges between (a) 4 and 12 dBA for sedans and vans; and (b) 2 and 5 dBA for trucks. Accordingly, these two ranges of sound level changes can be used to evaluate the performance of temporary rumble strips and examine if they can produce a similar auditory stimulus to alert inattentive drivers. This section analyzes the generated sound levels of nine test configurations of different types of temporary rumble strips at the edge of work zones and compares their performance to the aforementioned two ranges generated by permanent rumble strips, as shown in Figures 8.20, 8.21 and 8.22.

Table 8.7 Sound Levels of Permanent Rumble Strips.

Research Study	Generated Sound Level
Wood (1994)	6 dBA
Elefteriadoiu et al. (2000)	9~11 dBA
Caltrans (2001)	12 dBA for sedan, and 2~5 for heavy trucks
Outcalt (2001)	6~10 dBA
Miles and Finley (2007)	4 dBA

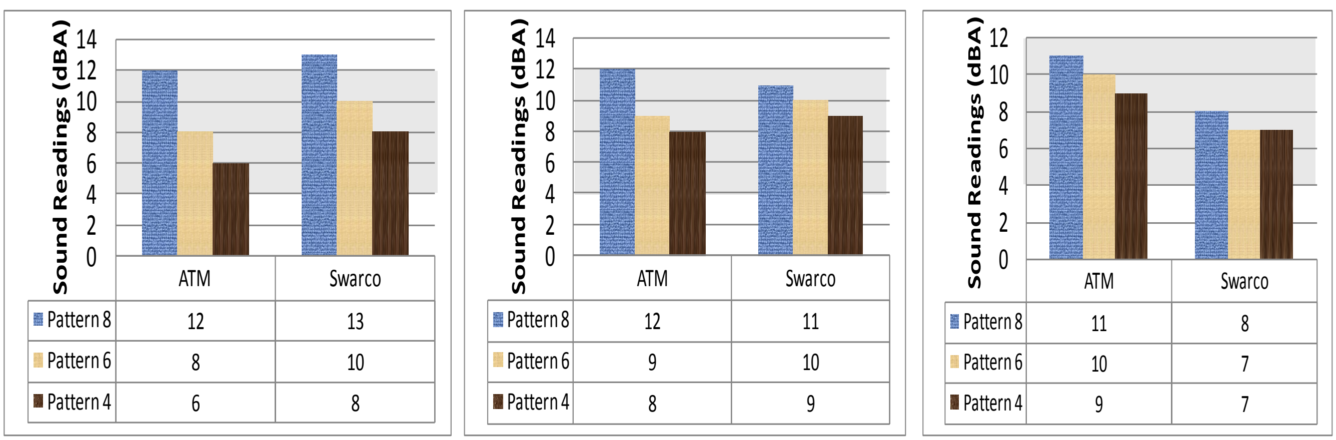
The findings of this analysis indicates that both types of tested temporary rumble strips (ATM and Swarco) at the edge of work zones generated adequate sound levels that are comparable to those produced by permanent rumble strips. For the tested sedan, Figure 8.20 illustrates the measured sound level change when the sedan was travelling at a speed of 30, 40 and 50 mph over the two types of temporary rumble strips that had a spacing of 12 inches and included a varying number of strips per set (4, 6 and 8). The results in this Figure illustrates that the measured sound levels for all these tested arrangements ranged from 5 to 16 dBA which indicates that the lower and upper bounds of these measurements exceeds the respective bounds reported in the literature for permanent rumble strips (4 to 12 dBA).

For the tested van, Figure 8.21 presents the measured sound level changes inside the van when it traveled at a speed of 30, 40 and 50 mph over the two types of temporary rumble strips that had a spacing of 12 inches and included a varying number of strips per set (4, 6 and 8). Similarly, the results of these experiments indicate that the measured sound levels for all these tested arrangements ranged from 6 to 13 dBA which indicates that the lower and upper bounds of these measurements also exceeds the respective bounds reported in the literature for permanent rumble strips (4 to 12 dBA). A similar performance was also observed for the tested truck that experienced measured sound levels for all these tested arrangements that ranged from 2 to 10 dBA which is similar to or exceeds the respective bounds reported in the literature for permanent rumble strips (2 to 5 dBA) for trucks, as shown in Figure 8.22. These results confirm the effectiveness of deploying temporary rumble strips at the edge of work zones in generating adequate sound levels to alert inattentive drivers that are similar to those of permanent rumble strips.



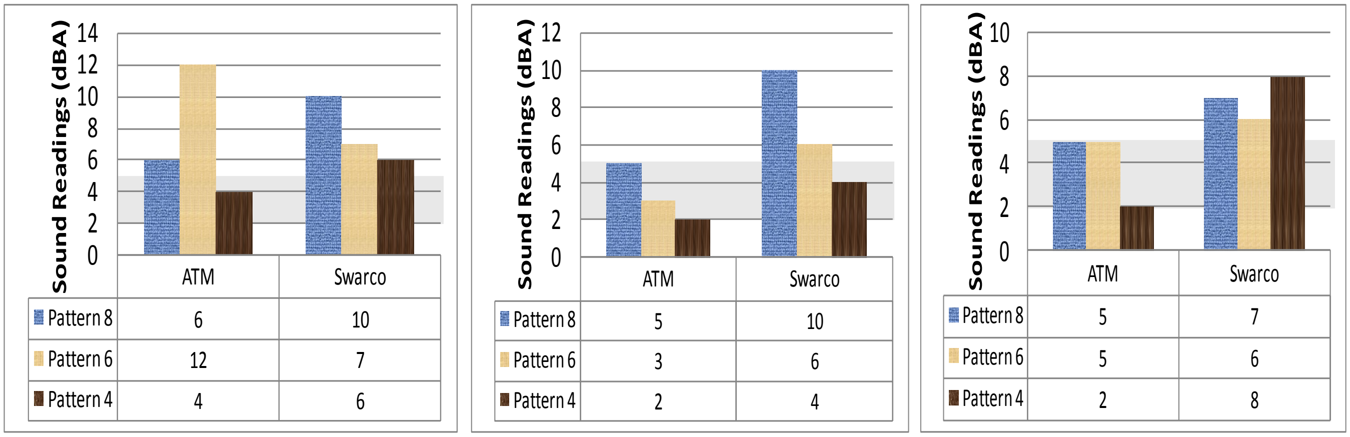
(a) **(b)** **(c)**

Figure 8.20 Change in sound level inside a sedan traversing rumble strips spaced at 12 inches at: (a) 30 mph; (b) 40 mph; and (c) 50 mph



(a) **(b)** **(c)**

Figure 8.21 Change in sound level inside a van traversing rumble strips spaced at 12 inches at: (a) 30 mph; (b) 40 mph; and (c) 50 mph



(a) **(b)** **(c)**

Figure 8.22 Change in sound level inside a truck traversing rumble strips spaced at 12 inches at: (a) 30 mph; (b) 40 mph; and (c) 50 mph

8.5.2 Correlation Analysis of Study Parameters and Change in Sound Levels

Two independent tests, Pearson Chi-Square and Likelihood Ration Chi-Square, were used to identify all possible correlations among rumble strips and vehicle parameters and the increase in sound levels. The findings of this correlation analysis are summarized in Table 8.8 that indicates the “sound level change” variable is correlated with four study parameters: (1) number of rumble strips per set; (2) type of rumble strips; (3) type of vehicle; and (4) vehicle speed. This indicates that these variables need to be carefully considered and analyzed during the design of temporary rumble strips that are placed at the edge of work zones under the wheels of one side of the vehicles driving next to the work zone. A detailed analysis of these four parameters is presented in the following sections.

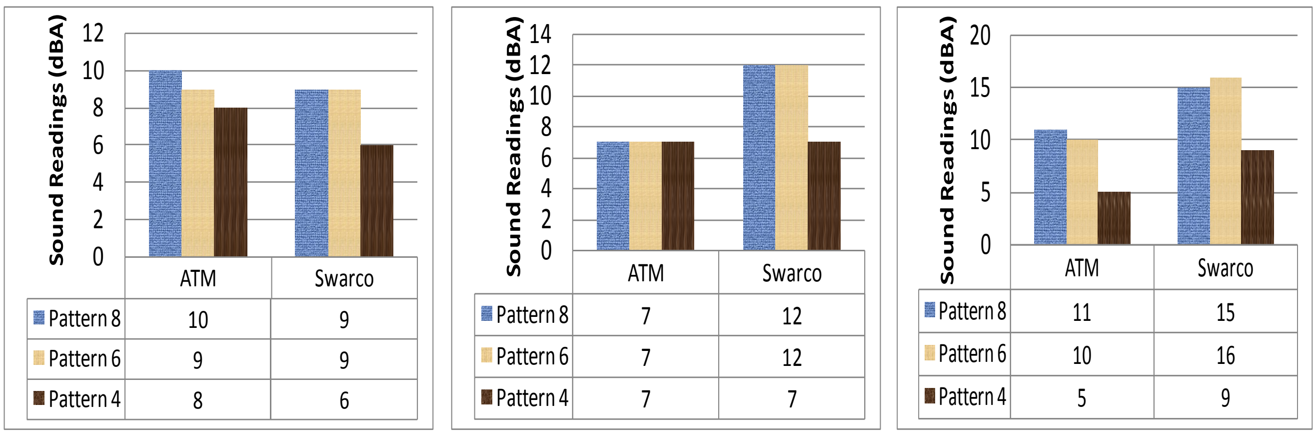
Table 8.8 Correlated Parameters of Rumble Strips Parameters at 5% significance level

Correlated Factors of Rumble Strips Auditory Stimulus		Pearson Chi-Square		Likelihood Ratio Chi-Square	
		P-Value	Related	P-Value	Related
Sound measurement	Number of strips per set	.0004	YES	<0.0001	YES
Sound measurement	Rumble strips spacing	0.9774	NO	0.9782	NO
Sound measurement	Rumble strips type	0.0048	YES	0.003	YES
Sound measurement	Vehicles speed	0.0318	YES	0.0158	YES
Sound measurement	Vehicles type	<0.0001	YES	<0.0001	YES

8.5.3 Impact of Number of Strips per Set

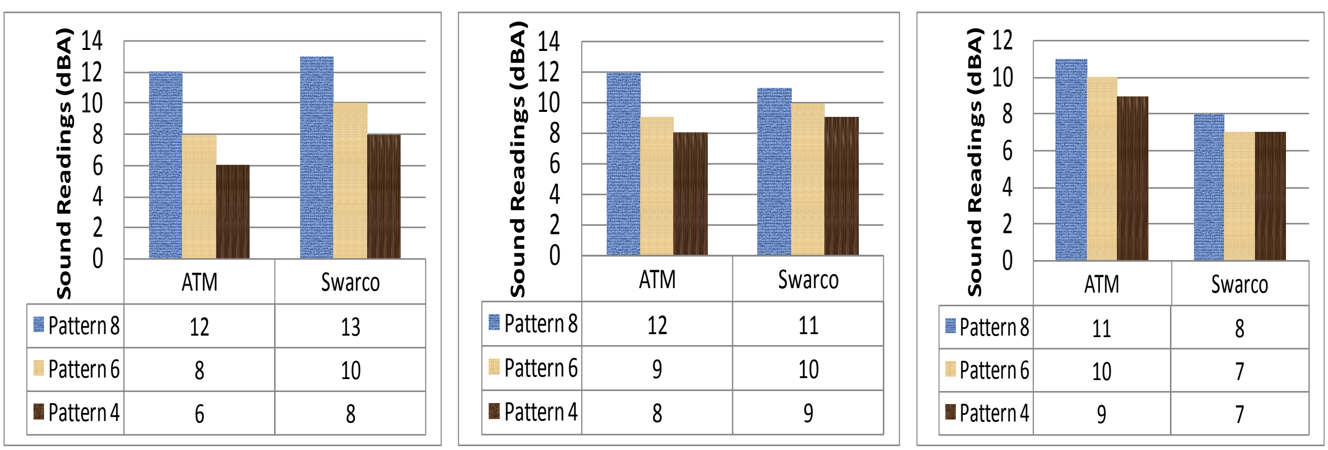
The number of strips per set (pattern) was found statistically correlated with the increase in sound level associated with the use of temporary rumble strips at the edge of work zones, as shown in Table 8.8. Based on the literature review and the recommendations of manufacturers, three pattern configurations were tested in the field experiments: 4 strips/set, 6 strips/set, and 8 strips/set. The two types of rumble strips, ATM and Swarco, were tested using these three patterns. Since the spacing of rumble strips was not found to be statistically correlated with the increase in sound levels, only the rumble strips spacing of 12 inches using different configurations is presented in Figures 8.23, 8.24, and 8.25. The records of other rumble strips spacing arrangements (24 and 36 inches) are listed in Appendix F.

The results of this analysis indicate that the sound level changes inside the sedan ranged between 5 dBA and 16 dBA and it generally increased as the number of strips per set increased, as shown in Figure 8.23. The minimum sound was measured for the configuration of 4 ATM strips/set while the maximum was recorded for the configuration of 6 Swarco strips/set when the sedan was traveling at a 50 mph speed. For the tested van, the minimum increase in sound level (6 dBA) was measured for the 4 strips/set pattern while the maximum increase in sound level (12 dBA) was observed for the 8 strips/set pattern for all the tested speeds, as shown in Figure 8.24. For the tested truck, at the results illustrate that the pattern of 4 strips per set produced the least increase in sound levels that ranged between 2 to 8 dBA, as shown in Figure 8.25.



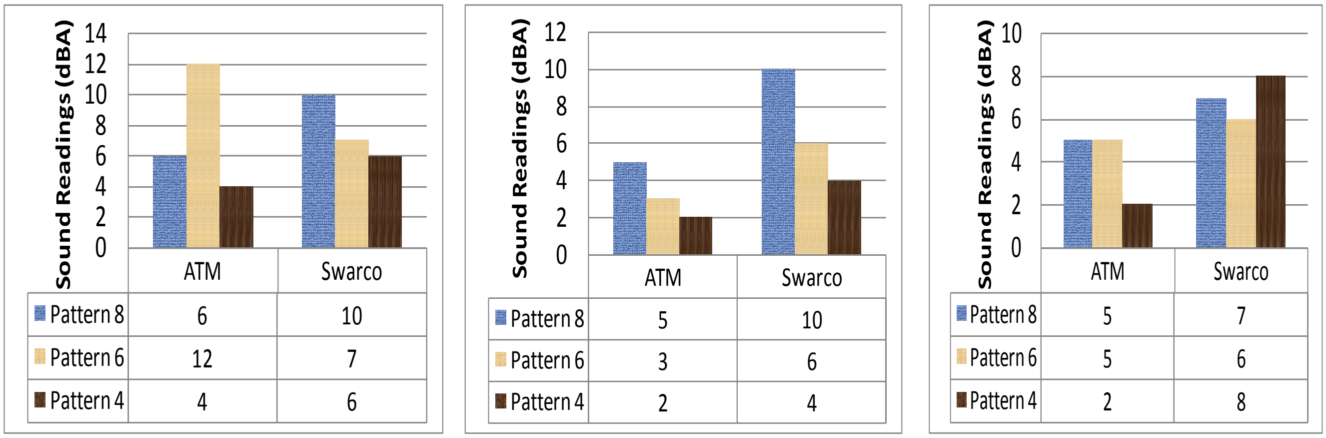
(a) **(b)** **(c)**

Figure 8.23 Change in sound level inside a sedan traversing rumble strips spaced at 12 inches at: (a) 30 mph; (b) 40 mph; and (c) 50 mph



(a) **(b)** **(c)**

Figure 8.24 Change in sound level inside a van traversing rumble strips spaced at 12 inches at: (a) 30 mph; (b) 40 mph; and (c) 50 mph

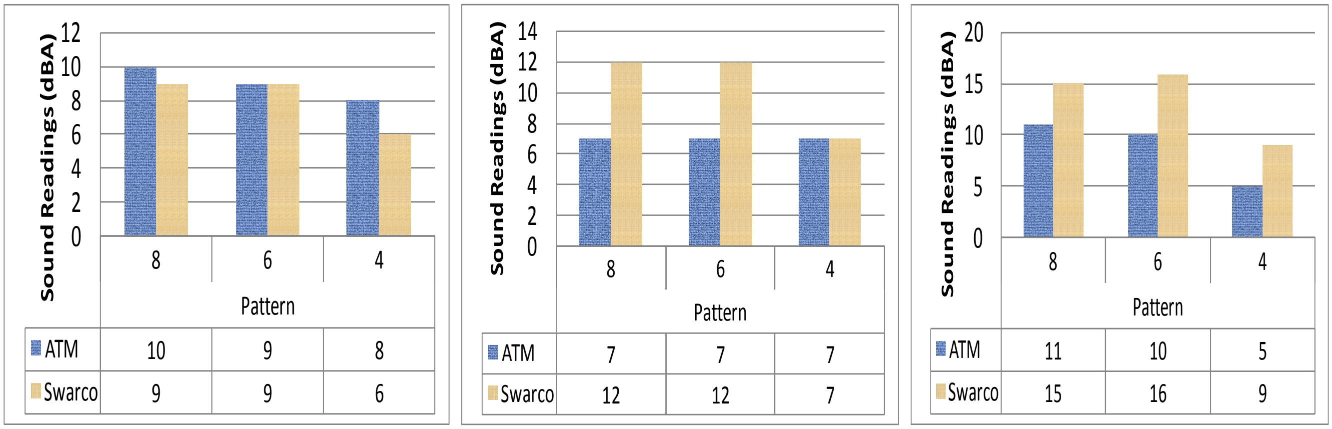


(a) **(b)** **(c)**

Figure 8.25 Change in sound level inside a truck traversing rumble strips spaced at 12 inches at: (a) 30 mph; (b) 40 mph; and (c) 50 mph

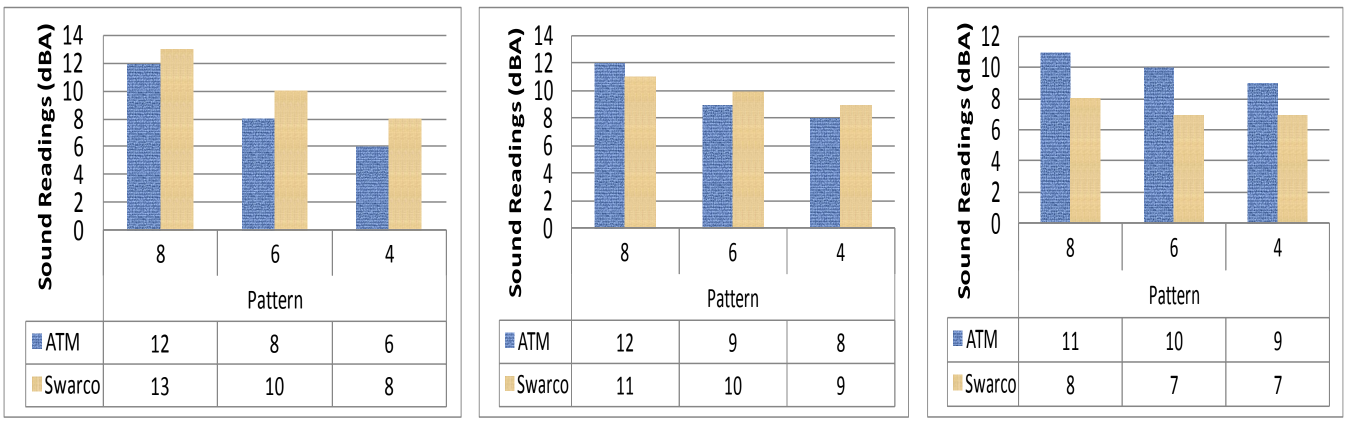
8.5.4 Impact of Rumble Strips Type

Two types of temporary rumble strips were tested in the field experiments: ATM and Swarco that had a length of 4 feet. The two types were tested using three patterns of 4 strips/set, 6 strips/set, and 8 strips/set. Figures 8.26, 8.27, and 8.28 illustrate the impact of rumble strips type on the generated sound levels for the tested rumble strips spacing of 12 inches. The records of other tested rumble strips spacing arrangements (24 and 36 inches) are listed in Appendix F. As shown in Figure 8.26 through Figure 8.28, the Swarco rumble strips generated higher sound levels than the ATM rumble strips in most test arrangements except for the sedan at 30 mph and the van at 50 mph. The highest sound level change (16 dBA) was measured for the Swarco strips while the least sound level change (2 dBA) was recorded for the ATM strips.



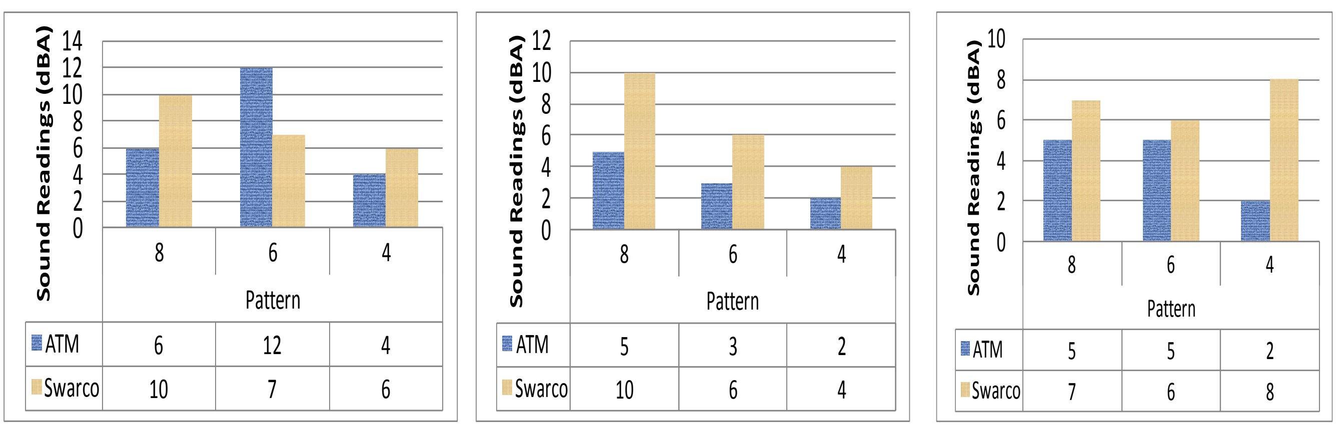
(a) **(b)** **(c)**

Figure 8.26 Change in sound level inside a sedan traversing rumble strips spaced at 12 inches at: (a) 30 mph; (b) 40 mph; and (c) 50 mph



(a) **(b)** **(c)**

Figure 8.27 Change in sound level inside a van traversing rumble strips spaced at 12 inches at: (a) 30 mph; (b) 40 mph; and (c) 50 mph

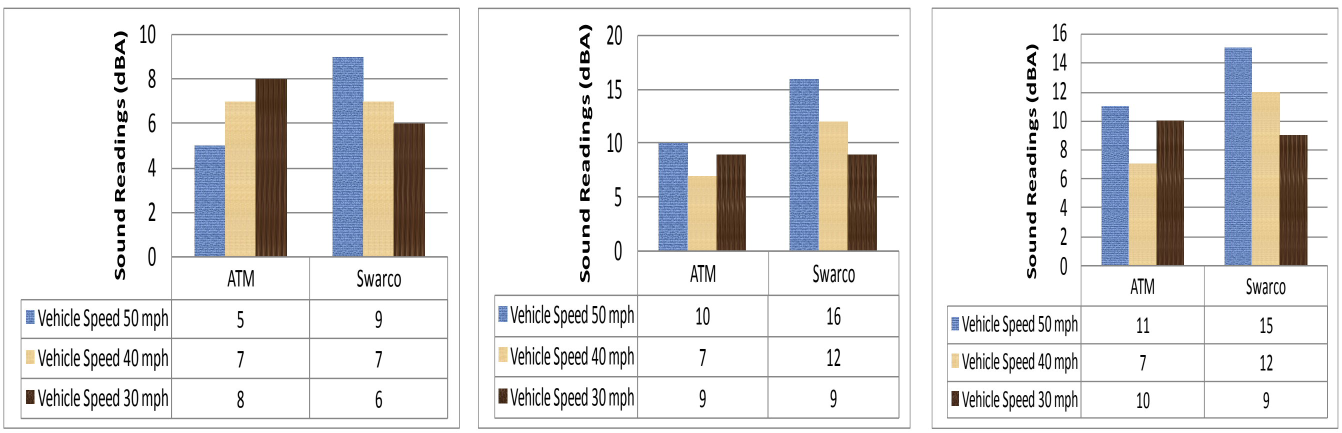


(a) **(b)** **(c)**

Figure 8.28 Change in sound level inside a truck traversing rumble strips spaced at 12 inches at: (a) 30 mph; (b) 40 mph; and (c) 50 mph

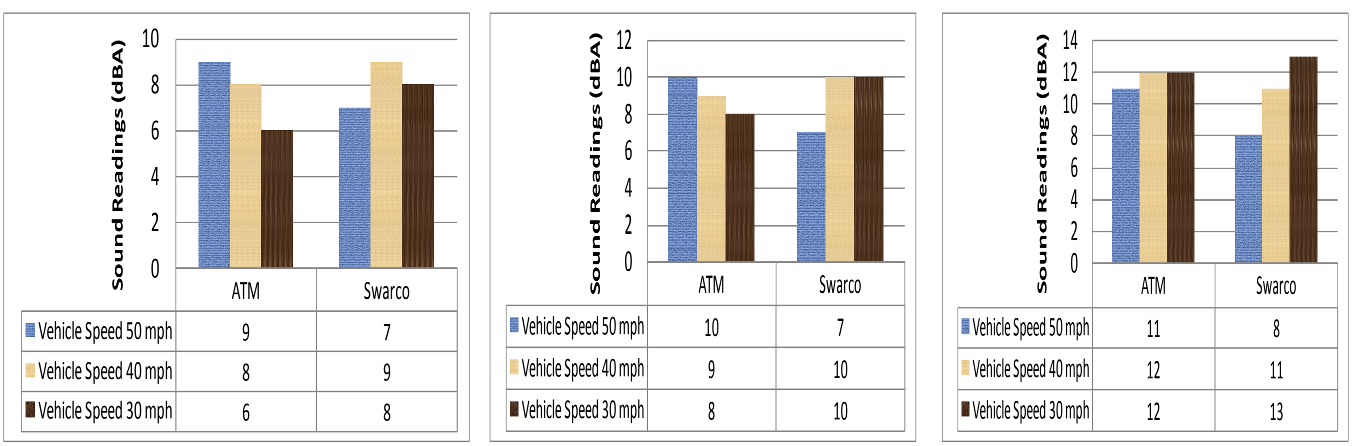
8.5.5 Impact of Vehicle Speed

The test vehicles were driven at 30, 40, and 50 mph along all the tested patterns of rumble strips. Figures 8.29, 8.30, and 8.31 illustrate the impact of vehicle speed on the generated sound levels for the tested rumble strips spacing of 12 inches. The records of other tested rumble strips spacing arrangements (24 and 36 inches) are listed in Appendix F. As shown in Figure 8.29, the sedan traveling over the ATM rumble strips at a speed of 50 mph generated higher sound levels than higher sedan speeds when the utilized rumble strips pattern was 6 and 8 strips per set.



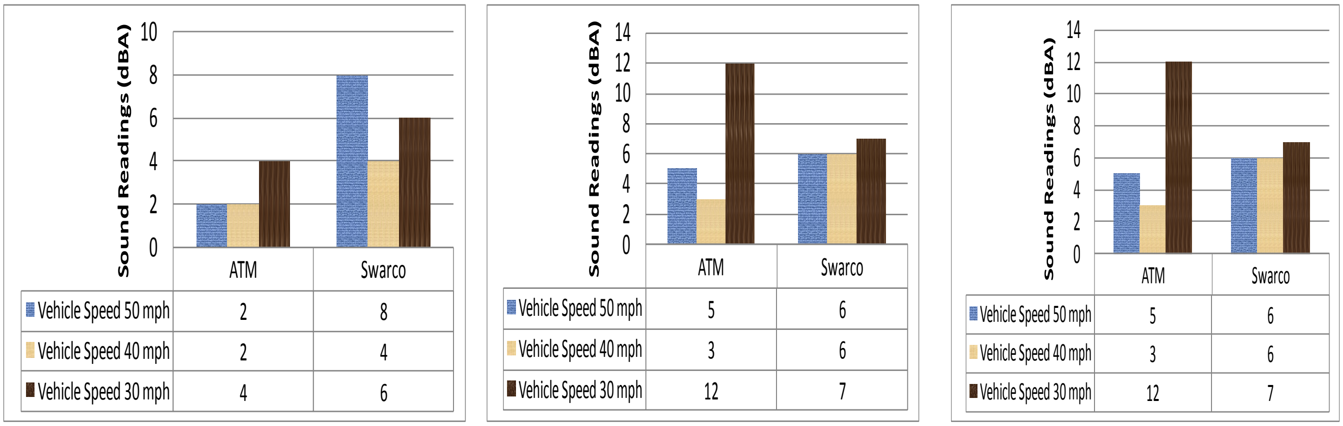
(a) **(b)** **(c)**

Figure 8.29 Change in sound level inside a sedan traversing rumble strips spaced at 12 inches of: (a) 4 strips/set; (b) 6 strips/set; and (c) 8 strips/set



(a) **(b)** **(c)**

Figure 8.30 Change in sound level inside a van traversing rumble strips spaced at 12 inches of: (a) 4 strips/set; (b) 6 strips/set; and (c) 8 strips/set

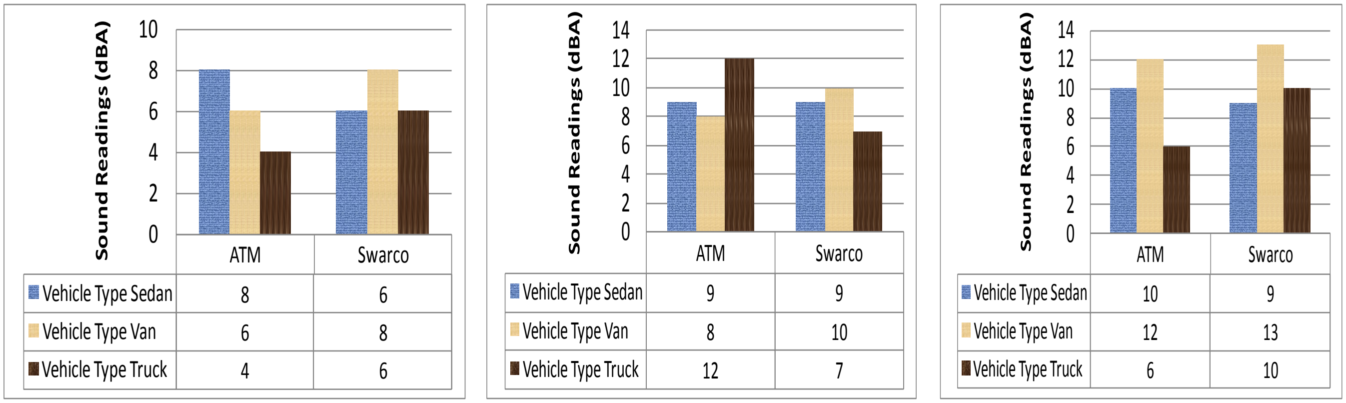


(a) **(b)** **(c)**

Figure 8.31 Change in sound level inside a truck traversing rumble strips spaced at 12 inches of: (a) 4 strips/set; (b) 6 strips/set; and (c) 8 strips/set

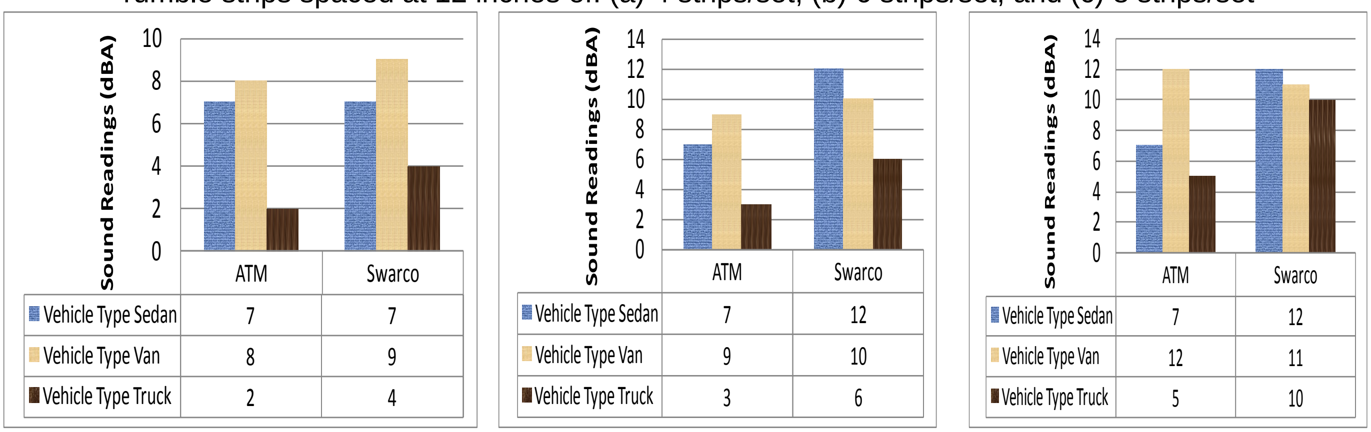
8.5.6 Impact of Vehicle Type

Three types of vehicles were tested during the field experiments: a sedan, a cargo van, and a 26-foot truck. Figures 8.32, 8.33, and 8.34 illustrate the impact of vehicle type on the generated sound levels for the tested rumble strips spacing of 12 inches. The results of other tested rumble strips spacing arrangements (24 and 36 inches) are listed in Appendix F. As shown in Figure 8.32 through Figure 8.34, both the sedan and the van generated sound levels higher than the 26-foot truck. Figure 8.33 also shows that the van generated the highest sound levels in most test cases when the travel speed was 40 mph. The minimum increase in sound level experienced by the sedan was 5 dBA and it was recorded when it traveled over 4 ATM rumble strips per set at a speed of 50 mph.



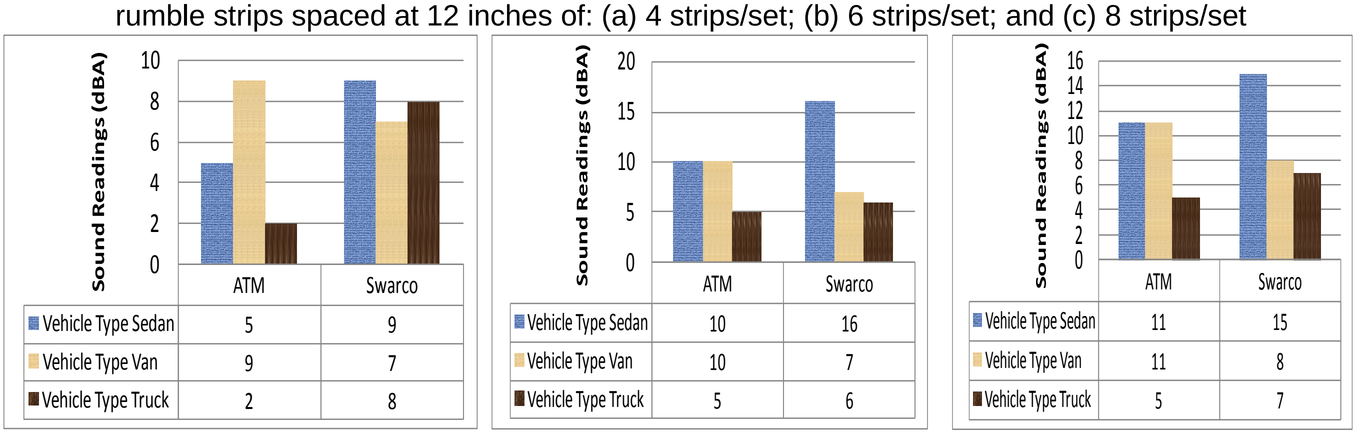
(a) **(b)** **(c)**

Figure 8.32 Change in sound level inside different vehicles traveling at 30 mph and traversing rumble strips spaced at 12 inches of: (a) 4 strips/set; (b) 6 strips/set; and (c) 8 strips/set



(a) **(b)** **(c)**

Figure 8.33 Change in sound level inside different vehicles traveling at 40 mph and traversing rumble strips spaced at 12 inches of: (a) 4 strips/set; (b) 6 strips/set; and (c) 8 strips/set



(a) **(b)** **(c)**

Figure 8.34 Change in sound level inside different vehicles traveling at 50 mph and traversing rumble strips spaced at 12 inches of: (a) 4 strips/set; (b) 6 strips/set; and (c) 8 strips/set

8.6 RECOMMENDATIONS TO IMPROVE THE UTILIZATION OF WORK ZONE TEMPORARY RUMBLE STRIPS

This section presents practical recommendations to improve the utilization of temporary rumble strips prior to and at the edge of work zones. The recommendations focus on: (1) the type of temporary rumble strips; (2) pattern of temporary rumble strips; (3) spacing of temporary rumble strips; (4) vehicle type; (5) vehicle speed; and (6) location of rumble strips. The recommendations of placing temporary rumble strips within work zone layout have been presented in Chapter 5 based on IDOT resident engineers' responses towards the last question of the survey which was "*If temporary rumble strips (6~8 strips/set) can be used prior to or at the edge of work zones, where do you recommend them to be placed within the work zone layout? Please explain why?*"

8.6.1 Temporary Ruble Strips Types

The findings of the conducted field experiments indicate that the three tested types of temporary rumble strips (ATM, Swarco, and RoadQuake) were effective in alerting inattentive drivers as they generated auditory stimulus that exceeded the typical levels of permanent rumble strips of 4 dBA. The results also show that the use of temporary rumble strips that have larger width and thickness increase their effectiveness as they are capable of generating higher sound levels. The results also show that the use of RoadQuake rumble strips at travelling speeds lower than 40 mph can cause excessive sound levels (higher than 20 dBA) especially for commercial trucks.

The efficiency and durability of temporary rumble strips is an important factor that should also be considered when determining the type to be used. The installation process time significantly varied according to the number of strips to be placed and the type of rumble strips as shown in Table 7.1. Types such as ATM and Swarco are not recommended to be multiply reused since they require multiple layers of adhesives to be installed which makes them difficult to be replaced in different locations. On the other hand, RoadQuake does not require any adhesives to be placed which makes it more manageable to be reused in different locations.

8.6.2 Temporary Rumble Strips Patterns

The findings of the field experiments indicate that the three tested patterns of 4 strips/set, 6 strips/set, and 8 strips/set can be used effectively to generate auditory stimulus enough to alert drivers. The results also show that the effectiveness of temporary rumble strips and their generated sound levels increased as the number of strips per set increased. Accordingly, the highest effectiveness of temporary rumble strips can be achieved when the pattern of 8 strips per set is used.

8.6.3 Temporary Rumble Strips Spacing

The findings of the conducted field experiments indicate that the three tested spacings of 12 inches, 24 inches, 36 inches can be used effectively to generate auditory stimulus to alert inattentive drivers. RoadQuake should be placed at 36 inches spacing because of its significantly larger dimensions to avoid vehicle sliding. However, the field experiments showed that sound level changes inside different vehicles decreased as the spacing of rumble strips increased. Accordingly, the spacing between rumble strips should not exceed 24 inches for strips that have a width of 4 and 6 inches, and spacing should be increased to 36 inches for wider rumble strips such as the RoadQuake that has a width of 12 inches.

8.6.4 Vehicle Type

The findings of the conducted field experiments indicate that drivers inside the three tested types of vehicles experience adequate auditory stimulus to alert them when they travel over different patterns of rumble strips at varying speed limits. Both the sedan and the van generated sound levels higher than the 26-foot truck. This finding recommends that special attention should be given to work zones on highways that have high commercial volumes since that the auditory stimulus inside the cabin of large trucks is less effective than those experienced inside the cabin of a sedan or a van.

8.6.5 Vehicle Speed

The findings of the field experiments indicate that the three test vehicles driven at 30, 40, and 50 mph generated auditory stimulus enough to alert drivers when traversing different patterns of rumble strips at varying speed limits. In general, vehicles travelling at a speed limit of 30 mph generated higher sound levels than those travelling at higher speed limits of 40 and 50 mph. These findings highlight the need to reduce work zone speed limits to maximize the effectiveness and benefits of using temporary rumble strips in work zones.

8.6.6 Location of Rumble Strips

Temporary rumble strips can be located: (1) at the edge of work zones; and/or (2) prior to work zones as shown in Figure 8.21. The findings of these field experiments confirmed that all tested types of temporary rumble strips at both locations generated adequate sound levels compared to those sound levels produced by permanent rumble strips. This highlights the potential safety benefits of temporary rumble strips if they are placed along the edges of construction work zones. This setup and location of temporary rumble strips is capable of improving safety and reducing crashes into the work area in a way similar to the safety benefits that are achieved when permanent rumble strips are used on roadways.

CHAPTER 9

CONCLUSIONS

9.1 CONCLUSIONS

The research study presented in this dissertation focused on analyzing and optimizing existing work zone practices and exploring the effectiveness and efficiency of innovative temporary rumble strips that can be used to minimize crashes in and around highway construction and maintenance projects. In order to achieve this goal, this research study focused on two main thrusts: (1) studying and identifying the impact of current work zone layout parameters on crash occurrence and associated work zone costs; and (2) analyzing the efficiency and effectiveness of utilizing innovative temporary rumble strips prior to and at the edge of work zones. A number of research developments were introduced to accomplish the objectives of this study, including: (1) creating novel crash severity indices to represent the probability of a work zone to encounter severe crashes; (2) developing new innovative metrics for estimating the monetary value of work zone crash costs; (3) formulating an innovative model for optimizing work zone setup parameters to minimize total work zone costs including agency, user delay, and expected crash costs; (4) analyzing the efficiency and constructability of various arrangements of new and innovative traffic control devices such as the use of temporary rumble strips prior to and at the edge of work zones; and (5) conducting a comprehensive statistical analysis of the effectiveness of temporary rumble strips in generating adequate sound levels to alert inattentive drivers.

First, a comprehensive analysis of work zone crashes was conducted to identify the probable causes and contributing factors of work zone crashes in Illinois. Crash frequency analyses were performed to investigate and compare the impact of work zone parameters on the frequency and severity of: (1) fatal work zone crashes; (2) multi-vehicle injury crashes; and (3) single-vehicle injury crashes. Correlation analysis was then conducted among all available work zone crash parameters to identify probable causes and contributing factors of work zone crashes. Three crash severity indices were also developed to represent the probability of a work zone to encounter (a) severe injury crashes; (b) multi-vehicle crashes; and (c) multi-injury crashes.

Second, the impact of work zone layout parameters on the risk of crash occurrence was quantified and modeled using the results of: (1) site visits to various types of work zones, and (2) an online survey on work zone practices to collect IDOT resident engineers' perceptions of the risk level associated with various work zone parameters. Various statistical analyses were performed to quantify the impact of work zone parameters on the risk of crash occurrence. A new metric was then developed to estimate the monetary value of work zone crash costs. The new metric is modeled based on the impact of work zone hazards that contribute to increasing the risk level of crash occurrence and the temporary traffic control policy adopted to mitigate that risk.

Third, a novel model for optimizing work zone setup was formulated to search for and identify an optimal solution for five decision variables: work zone segment length, work zone speed limit, operation starting time, type of TTC, and barrier type. The model provides the capability of minimizing the total work zone cost of short- and long-term highway work zones which integrates three new metrics that are designed to calculate agency cost, user delay cost, and crash cost. The three cost metrics were modeled to estimate work zone costs at each construction hour using hourly traffic flow data. The optimization model was implemented using genetic algorithms (GAs) in a C++ objected oriented environment.

Fourth, field experiments on temporary rumble strips were conducted to analyze the efficiency and constructability of various arrangements prior to and at the edge of work zones. During these experiments, a total of 27 different arrangements of temporary rumble strips were tested at the Illinois Center for Transportation (ICT) in the University of Illinois at Urbana-Champaign. The installation and removal process of three different types of temporary rumble strips were analyzed and new prototypes of utilizing temporary rumble strips at the edge of work zone were developed.

Fifth, the effectiveness of temporary rumble strips in generating adequate sound levels to alert inattentive drivers was evaluated. A total of 351 sound level readings that represented different configurations of study parameters were collected and analyzed to: (1) identify the impact of temporary rumble strips geometries and vehicle characteristics on the generated sound levels; and (2) develop practical guidelines to improve the effectiveness of utilizing temporary rumble strips in work zones.

The aforementioned research developments contribute to the advancement of current and future practices in highway construction and maintenance projects and can lead to: (1) improve work zone safety for both the travelling public and construction workers; (2) improve current work zone layouts, strategies, and standards; (3) provide a baseline for controlling the risk of crash occurrence due to highway work zones; (4) assist traffic engineers planning optimal and safe work zone setups for highway construction; (5) direct the development of practical recommendations for efficient and effective design arrangements of temporary rumble strips; and (6) reduce work zone crashes in the work area through the implementation of practical temporary rumble strips arrangements.

9.2 RESEARCH CONTRIBUTIONS

The contributions of this research include:

1. Development of crash severity indices to represent the probability of a work zone to experience severe crashes. The work zone crash severity indices represent the probability of a work zone to encounter (a) severe injury crashes; (b) multi-vehicle crashes; and (3) multi-injury crashes. Crash severity indices were developed based on the advanced statistical analysis of the contributing factors that cause injury and fatal work zone crashes.
2. Development of a novel metric for estimating the monetary value of work zone crash costs. The new metric was modeled based on: (a) the impact of work zone hazards that contribute to increasing the risk level of crash occurrence; and (b) the temporary traffic control policy adopted to reduce that risk. The impact of work zone hazards was quantified using the results of: (i) site visits to various types of work zones, and (ii) an online survey on work zone practices to collect IDOT resident engineers' perceptions of the risk level associated with various work zone parameters the analysis.
3. Development of an innovative optimization model to minimize total work zone costs including agency/construction cost; user delay cost; and work zone crash cost. The new model was developed to optimize five work zone setup

parameters: (a) work zone segment length; (b) work zone speed limit; (c) starting time; (d) Temporary Traffic Control (TTC) policy; and (e) barrier type. Three new cost metrics were modeled to estimate work zone costs at each construction hour using hourly traffic flow data. The optimization model was implemented using genetic algorithms (GAs) in a C++ objected oriented environment.

4. Comprehensive analysis of the efficiency and constructability of various arrangements of new and innovative utilization of temporary rumble strips prior to and at the edge of work zones. The installation and removal processes of three different types of temporary rumble strips were analyzed and new prototypes of temporary rumble strips at the edge of work zone were developed.
5. Comprehensive statistical analysis of the effectiveness of temporary rumble strips in generating adequate sound levels to alert inattentive drivers. The statistical analysis was performed for 351 sound level readings that represented different configurations of study parameters. The results of the analysis led the development of practical guidelines to improve the effectiveness of utilizing temporary rumble strips in work zones.

9.3 RECOMMENDATION FOR FUTURE RESEARCH

This research study created new knowledge on the risks and probable causes of work zone crashes, and developed novel models for optimizing the utilization of existing work zone safety measures. The study also investigated the efficiency and effectiveness of utilizing innovative safety measures such as temporary rumble strips prior to and at the edge of work zones. Despite the significance and contributions of these research developments, future research and expansion of this study is recommended in a number of areas, including: (1) investigating the practicality and effectiveness of utilizing new prototypes of temporary rumble strips at the edge of work zones; (2) optimizing the layout and utilization of temporary rumble strips prior to and at the edge of work zones; and (3) improving safety of construction equipment entering and exiting work zones.

9.3.1 Evaluating the Practicality of Utilizing New Prototypes of Temporary Rumble Strips

This study evaluated the efficiency and effectiveness of utilizing temporary rumble strips at the edge of a hypothetical work zone as discussed in Chapter 7. This location of temporary rumble strips can be used to alert inattentive drivers if they encroach into the work area in a similar way that the permanent rumble strips are used to alert inattentive drivers when they drift off the road. This new approach of deploying temporary rumble strips of small lengths (2~4 feet) has the potential to be applied along construction work zones and significantly decrease the percentage of work zone crashes. All testing configurations of temporary rumble strips at the edge of work zones were proven effective in generating adequate sound levels sufficient to alert motorists. Despite their proven effectiveness, the installation and redeployment of temporary rumble strips at the edge of work zones can still be a challenging and costly task for construction crews. To address this critical constructability challenge, two new temporary rumble strips prototypes were developed: (1) ladder prototype; and (2) drum prototype to facilitate their installation and removal processes as shown in Figures 9.1and 9.2.

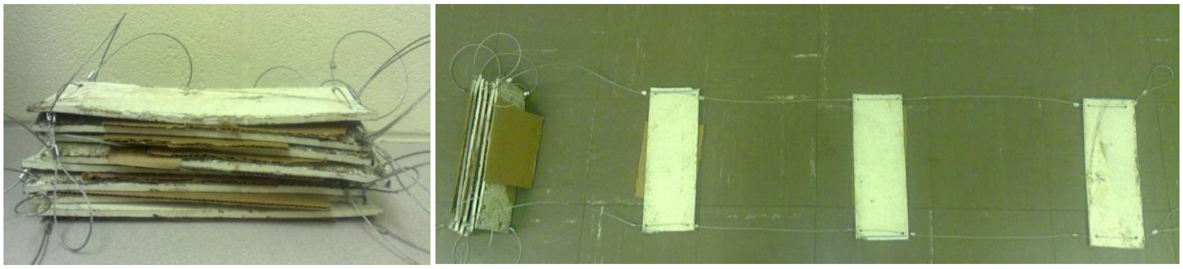


Figure 9.1 Temporary rumble strips at the edge of work zone (Ladder Prototype)

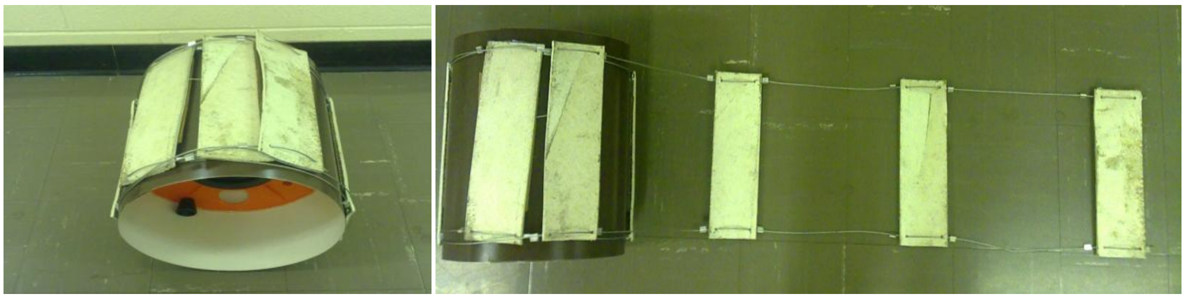


Figure 9.2 Temporary rumble strips at the edge of work zone (Drum Prototype)

These novel and promising prototypes of temporary rumble strips at the edge of work zones needs additional research to evaluate their constructability, safety and effectiveness. This evaluation needs to be performed in actual construction work zones in order to evaluate (1) the constructability and practicality of installing, removing, and redeploying these newly designed prototypes; (2) the safety of construction crews installing and removing these prototypes while allowing traffic to flow in adjacent open traffic lanes; and (3) the effectiveness of these prototypes in generating adequate sound levels to alert inattentive drivers. This proposed future research of these promising prototypes and deployment procedure of temporary rumble strips is expected to significantly reduce work zone crashes in and around work zones.

9.3.2 Optimizing Temporary Rumble Strips Layout

Field experiments on temporary rumble strips were conducted to analyze the efficiency and constructability of various arrangements prior to and at the edge of work zones. A total of 351 sound level readings that represented different configurations of study parameters were collected and analyzed to identify the impact of temporary rumble strips geometries and vehicle characteristics on the generated sound levels. Opportunities exist in expanding the research work completed in this study to develop a multi-objective optimization model that generates optimal trade-offs between the conflicting temporary rumble strips layout objectives of maximizing layout effectiveness and constructability while minimizing layout life cycle cost. This will require the development of new metrics to quantify (1) the layout effectiveness based on the generated sound level; (2) the layout constructability based on time required for the installation and removal processes; and (3) total temporary rumble strips life cycle cost considering material, labor, and maintenance costs. These metrics need to be integrated using advanced computing tools to provide optimal trade-offs between maximizing temporary rumble strips layout effectiveness while minimizing layout life cycle cost.

9.3.3 Improving Safety of Construction Equipment Entering Work Zones

Construction equipment and delivery trucks need to frequently enter and exit the work zone from adjacent open traffic lanes. These equipment and trucks have to slow down and in many cases almost stop to get into the closed work zone lanes which increase the risk of crashes with other vehicles traveling in the open traffic lanes. IDOT resident engineers have identified work zone setup/access to have the highest risk level of crash occurrence that threatens both public and construction workers lives (Chapter 5). In order to control and minimize this significant hazard, there is a pressing need to (1) analyze the frequency and probable causes of these types of work zone crashes considering all work zone hazard parameters; (2) study and recommend improvements in work zone layouts to ensure the safe entry and exit of construction equipment and delivery trucks to and from the work zone; and (3) analyze and recommend innovative temporary traffic control countermeasures to control and minimize this hazard. Improving the safety of work zone setup/access will lead to significant reduction in the number of crashes during both daytime and nighttime work zones. Moreover, this will significantly improve safety for (1) delivery truck drivers and construction equipment operators entering and exiting the work zone; and (2) the traveling public in adjacent open traffic lanes.

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APPENDIX A

CRASH VARIABLE TABLES

Table A.1 Observations for Time Data (Time of the Accident)/(AccHour)

Variable	Number	Description
Time of the accident: indicates the time period in which an accident occurred.	1	6:01AM: 10:00 (Morning peak hours)
	2	10:01:16:00 (Daytime non-peak hours)
	3	16:01 : 20:00 (Afternoon peak hours)
	4	20:01 : 6:00AM (Nighttime hours)

Table A.2 Observations for Time Data (Day of the Week)

Variable	Number	Description
Day of week: indicates the day of the week on which the crash occurred.	1	Monday
	2	Tuesday
	3	Wednesday
	4	Thursday
	5	Friday
	6	Saturday
	7	Sunday

Table A.3 Observations for Crash Data (Type of Collision)

Variable	Number	Description
Type of Collision: indicates the type of crash.	00, 99	Not stated, Unknown
	1	Pedestrian
	2	Pedalcyclists
	3	Train
	4	Animal
	5	Overturned
	6	Fixed object
	7	Other object
	8	Other non-collision
	9	Parked motor vehicle
	10	Turning
	11	Rear-end
	12	Sideswipe—same direction
	13	Sideswipe—opposite direction
	14	Head-on
	15	Angle

Table A.4 Observations for Road Data (Class of Trafficway)

Variable	Number	Description
Class of trafficway : indicates the classification of the road where the crash occurred.	0	Rural—unmarked state highway
	1	Rural—controlled access highway
	2	Rural—other marked state highway
	3	Rural—county/local road
	4	Rural—toll road
	5	Urban—controlled access highway
	6	Urban—other marked state highway
	7	Urban—unmarked state highway
	8	Urban—city street
	9	Urban—toll road

Table A.5 Observations for Road Data (Federal Classification of Highway)

Variable	Number	Description
Federal Classification of Highway: indicates the federal classification of the roadway where the crash occurred.	01,10	Interstate (not on National Highway System)
	02,20	Freeway/expressway (not on National Highway
	03,30	Major principal arterial (not on National Highway
	04,40	Minor arterial (not on National Highway System)
	05,50	Major collector (not on National Highway System)
	06,60	Minor collector (not on National Highway System)
	07	Local road (not on National Highway System)
	11	Interstate (on National Highway System)
	12	Freeway/expressway (on National Highway System)
	13	Major principal arterial (on National Highway
	14, 70	Minor arterial (on National Highway System)
	15	Major collector (on National Highway System)
	16	Minor collector (on National Highway System)
	17, 90	Local road (on National Highway System)

Table A.6 Observations for Road Data (Road Condition)/(TypeConstruction)

Variable	Number	Description
Road Condition: indicates a deficiency in the road where the crash occurred.	0	Not stated
	1	No defects
	2	Construction zone
	3	Maintenance zone
	4	Utility work zone
	5	Work zone—unknown
	6	Shoulders
	7	Ruts/holes
	8	Worn surface
	9	Debris on roadway
	10	Other
	99	Unknown

Table A.7 Observations for Road Data (Road Surface)/(RoadSurfaceCond)

Variable	Number	Description
Road surface: indicates the road surface condition at the scene of the crash.	0	Not stated
	1	Dry
	2	Wet
	3	Snow/slush
	4	Ice
	5	Sand/mud/dirt/etc.
	6	Other
	9	Unknown

Table A.8 Observations for Road Data (Route Prefix)

Variable	Number	Description
Route Prefix: indicates the route where the crash occurred.	0	Not applicable
	1	U.S. route
	2	Interstate business loop
	3	U.S. business route
	4	Bypass (in 1996, also means U.S. one-way couple)
	5	Illinois route
	6	Illinois alternate route (in 1996 also means Illinois one-way couple)
	7	Illinois business route (in 1996 also means interstate business loop one way couple)
	8	Non-marked route
	9	Interstate

Table A.9 Observations for Road Data (Traffic Control)

Variable	Number	Description
Traffic Control: indicates the type of traffic signals or restrictions at the scene of the crash.	0	Not stated
	1	No traffic control
	2	Stop sign or red flasher
	3	Traffic control signal
	4	Yield sign or yellow flasher
	5	Police officer or flagman
	6	Railroad crossing gate
	7	Other railroad crossing device
	8	School speed zone
	9	No passing zone
	10	Other type regulation sign
	11	Other warning sign
	12	Lane use control marking
	13,99	Other, Unknown

Table A.10 Observations for Road Data (Traffic Control Functionality)

Variable	Number	Description
Traffic Control Functioning: indicates the type of traffic control functioning at the scene of the crash.	0	Not stated
	1	No traffic control
	2	Not functioning
	3	Functioning improperly
	4	Functioning properly
	5	Reflecting material worn
	6	Missing
	7	Other
	8	Unknown

Table A.11-A Observations for Contributing Causes (Cause 1 &2)

Variable	Number	Description
Contributing cause: Indicate the actions of the driver that contributed to the crash.	00	Not stated
	01	Exceeded authorized speed limit
	02	Right-of-way
	03	Following too closely
	04	Overtaking/passing
	05	Wrong side/way
	06	Improper turn/no turn signal
	07	Right turn on red
	08	Under the influence of alcohol/drugs (used when arrest is effected)

Table A.11-B Observations for Contributing Causes (Cause 1 &2)

Variable	Number	Description
Contributing cause (Cont.): Indicate the actions of the driver that contributed to the crash.	09	Operated vehicle in erratic, reckless, careless, negligent or aggressive manner
	10	Equipment—vehicle condition
	11	Weather
	12	Road engineering/surface/markings/defects
	13	Road construction
	14	Vision obscured (signs, tree limbs, buildings, etc.)
	15	Driving skills, knowledge, experience
	16	Driver distraction/inattention
	17	Physical condition of driver
	18	Unable to determine
	19	Had been drinking (used when arrest is not made)
	20	Improper lane usage
	21	Swerved due to animal, object, non-motorist
	22	Disregarded yield sign
	28	Failure to reduce speed to avoid crash
	29	Passed stopped school bus
	30	Improper backing
	31	Electronic equipment, i.e. cellular phone

Table A.12 Observations for Contributing Causes (Categorized Contributing Causes)

Categorized Contributing Causes	Number	Description (See Table 11-A & 11-B)
Improper Driving	1	2,3,4,5,6,7,8,9,10,15,16,17,19,29,30
Distraction	2	31
Work Zone Environment	3	11,12,13,14,20,21
Disregarded Traffic Control	4	22,23,24,25,26
Unknown	5	0,18
Speed	6	1,27,28

Table A.13 Observations for Light and Weather Data (Light Condition)

Variable	Number	Description
Light Condition: indicates the general light conditions prevailing at the time of the crash.	0, 9	Not stated
	1	Daylight
	2	Dawn
	3	Dusk
	4	Darkness
	5	Darkness—road lighted

Table A.14 Observations for Light and Weather Data (Weather)

Variable	Number	Description
Weather: indicates the weather conditions at the time of the crash.	0	Not stated, Unknown
	1	Clear
	2	Rain
	3	Snow
	4	Fog/smoke/haze
	5	Sleet/hail
	6	Severe crosswind
	7	Other

Table A.15 Observations for Severity

Variable	Number	Description
SEV_CDE: indicates the crash severity	0	Not Coded
	01	Fatal
	02	Injury
	03	Property Damage Only

Table A.16 Observations for InjurySeverity

Variable	Number	Description
Weather: indicates the severity of the collision	0	No injury
	1	Injury other than fatal requiring hospitalization
	2	Injury evident to others at scene
	3	No visible injury (possible)
	4	Fatal

Table A.17 Observations for RoadClassification

Variable	Number	Description
Road Classification: indicates the classification of the roadway in which the accident occurred	01	Urban freeways
	02	Urban freeways < 4 lanes
	03	Urban 2 lane roads
	04	Urban multilane divided non-freeways
	05	Urban multilane undivided non-freeways
	06	Rural freeways
	07	Rural freeways < 4 lanes
	08	Rural 2 lane roads
	09	Rural multilane divided non-freeways
	10	Rural multilane undivided non-freeways
	99	Others

Table A.18 Observations for OnewayIndicator

Variable	Number	Description
OnewayIndicator: indicates the travel direction of the roadway	1	One-way
	2	Two-way
	3	One-way reversible
	4	Two-way reversible

Table A.19 Observations for IntersectionRel

Variable	Number	Description
IntersectionRel: indicates whether the accident occurred at an intersection or not	1	Yes
	2	No
	0	Not states

Table A.20(A) Observations for SurfaceType

Variable	Number	Description
SurfaceType : Indicates the type of the roadway surface	010	Natural surface, not conforming to graded and drained earth road requirements
	020	Natural earth, graded with drainage
	100	Without dust palliative treatment
	110	With dust palliative
	200	Without dust palliative treatment
	210	With dust palliative treatment
	300	Bituminous surface treated

Table A.20(B) Observations for SurfaceType

Variable	Number	Description
SurfaceType : Indicates the type of the roadway surface	400	Mixed bituminous (low type bituminous)
	410	Bituminous penetration
	500	High type bituminous (flexible base)
	550	Bituminous concrete, sheet or rock asphalt
	600	PCC – reinforcement unknown
	610	PCC – no reinforcement
	620	PCC – partial reinforcement
	630	PCC – full reinforcement
	640	PCC – continuous reinforcement
	650	Brick, block, steel, or like material
	700	PCC – reinforcement unknown
	710	PCC – no reinforcement
	720	PCC – partial reinforcement
	730	PCC – full reinforcement
	740	PCC – continuous reinforcement
	800	Brick, block or other
	900-999	Various combination surface types

Table A.21 Observations for MedianType

Variable	Number	Description
MedianType: indicates the roadway median type	0	No median
	1	Unprotected – sodded, treated earth
	2	Curbed - raised median, any width
	3	Positive barrier – fencing, retaining walls, guard rails, open spaces between elevated
	4	Rumble strip or chatter bar
	5	Painted
	6	Bi-directional turn lanes, painted
	7	Mountable median

Table A.22 Observations for MedianWidth

Variable	Number	Description
MedianWidth: indicates the roadway median width categorized in	No width	1
	01-05	2
	06-10	3
	11-30	4
	31-50	5
	51-100	6
	101-999	7

Table A.23 Observations for AADT

Variable	Number	Description
AADT: indicates the annual average daily traffic of the roadway	1	Below 10,000
	2	10,000 ~ 20,000
	3	20,000~30,000
	4	30,000 ~ 40000
	5	40,000 ~ 50,000
	6	Over than 50,000

Table A.24 Observations for MultipleDailyVolume

Variable	Number	Description
MultipleDailyVolume: indicates the multiple daily volume of the roadway	1	Below 2000
	2	2000 ~ 4000
	3	4000 ~ 6000
	4	6000 ~ 8000
	5	8000 ~ 10000
	6	Over than 10000

Table A.25 Observations for CommercialVolume

Variable	Number	Description
CommercialVolume: indicates the annual average daily traffic of the roadway	1	Below 2000
	2	2000 ~ 4000
	3	4000 ~ 6000
	4	6000 ~ 8000
	5	8000 ~ 10000
	6	Over than 10000

Table A.26 Observations for MilVehMiTrv

Variable	Number	Description
MilVehMiTrv: indicates the million vehicle mile travel of the roadway	1	Below 1.736
	2	1.736~ 3.472
	3	3.472~ 5.208
	4	5.208~ 6.944
	5	6.944~ 8.68
	6	Over than 8.68

APPENDIX B

SURVEY ON WORK ZONE PRACTICES

SURVEY OF IDOT WORK ZONE PRACTICES

The Illinois Center of Transportation and IDOT are sponsoring an ongoing research project that aims to study and recommend strategies to minimize the severity and frequency of traffic-related work zone crashes in Illinois. Your valuable feedback is needed to complete this online survey that is designed to take **less than 10 minutes.**

In order to objectively evaluate and control the risk of work zone crashes in Illinois, please identify the risk level associated with each work zone parameter listed in the survey. We would appreciate if you can complete the survey by February 15, 2010.

Your thorough and candid responses are critical to the accuracy and richness of information gathered. Thank you in advance for your time!

If you have any questions or comments, please contact the PI of this project (Khaled El-Rayes).

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SURVEY OF IDOT WORK ZONE PRACTICES

Contact Infomation*

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1- Risk Level of **Work Zone Layout** on Crash Occurrence

	Lowest Risk 1	2	Medium Risk 3	4	Highest Risk 5
1.1 Multilane Closure at Entrance Ramp	○	○	○	○	○
1.2 Multilane Closure at Exit Ramp	○	○	○	○	○
1.3 Two Lane Closure on Freeway/Expressway	○	○	○	○	○
1.4 One Lane Closure on Freeway/Expressway	○	○	○	○	○
1.5 Median Crossover	○	○	○	○	○
1.6 Divergence	○	○	○	○	○
1.7 Use of Shoulder	○	○	○	○	○

2- Risk Level of **Work Zone Hours** on Crash Occurrence

	Lowest Risk 1	2	Medium Risk 3	4	Highest Risk 5
2.1 Morning (6:01AM ~10:00AM)	○	○	○	○	○
2.2 Daytime (10:01AM ~ 4:00PM)	○	○	○	○	○
2.3 Afternoon (4:01PM ~ 8:00PM)	○	○	○	○	○
2.4 Night (8:01PM ~ 6:00AM)	○	○	○	○	○

3- Risk Level of **Work Zone Duration** on Crash Occurrence

	Lowest Risk 1	2	Medium Risk 3	4	Highest Risk 5
3.1 Long Term Stationary Operations (D ≥ 3 days)	○	○	○	○	○
3.2 Intermediate Term Stationary Operations (1 day > D > 3 days)	○	○	○	○	○
3.3 Short Term Stationary Operations (D > 30 minutes)	○	○	○	○	○
3.4 Mobile Operations (D < 15 minutes)	○	○	○	○	○

4- Risk Level of using **Right-side or Median Shoulder** as a temporary traffic lane on Crash Occurrence

	Lowest Risk 1	2	Medium Risk 3	4	Highest Risk 5
4.1 Narrow Shoulders and Lane Constricted	○	○	○	○	○
4.2 Full Shoulders and Lane Constricted	○	○	○	○	○
4.3 Shoulder Pavement Structure is Different	○	○	○	○	○
4.4 High Traffic Volume	○	○	○	○	○
4.5 Lane Constricted by Temporary Concrete Barriers	○	○	○	○	○

5- Risk Level of **Work Zone Type** on Crash Occurrence

	Lowest Risk 1	2	Medium Risk 3	4	Highest Risk 5
5.1 Work Zone Setup/Access	○	○	○	○	○
5.2 Shoulder Closure Only Operations	○	○	○	○	○
5.3 Pavement Sawing/Patching	○	○	○	○	○
5.4 HMA Paving	○	○	○	○	○
5.5 Bridge/Culvert Construction and Maintenance	○	○	○	○	○
5.6 Pavement Striking and Marking	○	○	○	○	○
5.7 Delivery Truck Entrance/Exit	○	○	○	○	○

6- Risk Level of **Roadway Classification** on Crash Occurrence

	Lowest Risk 1	2	Medium Risk 3	4	Highest Risk 5
6.1 Controlled Access Highways	○	○	○	○	○
6.2 Multilane Rural without Access Control	○	○	○	○	○
6.3 Two Lanes	○	○	○	○	○
6.4 Urban and Suburban Arterials	○	○	○	○	○

7- Risk Level of **Reduced Lane Width** on Crash Occurrence

	Lowest Risk 1	2	Medium Risk 3	4	Highest Risk 5
7.1 All Lanes Open for Traffic (Off-Road Operations)	○	○	○	○	○
7.2 One or More Lanes Closed (Traffic Lane Width = 12 ft)	○	○	○	○	○
7.4 One or More Lanes Closed (Traffic Lane Width < 12 ft)	○	○	○	○	○
7.5 Pavement Edge Drop-off	○	○	○	○	○

8- Risk of **Median Type** on Crash Occurrence at Work Zones

	Lowest Risk 1	2	Medium Risk 3	4	Highest Risk 5
8.1 No Median	○	○	○	○	○
8.2 Unprotected - Sodded, Treated Earth	○	○	○	○	○
8.3 Curbed - Raised Median, Any Width	○	○	○	○	○
8.4 Positive Barrier - Fencing, Retaining Walls, Guard Rails, Open Space Between Elevated	○	○	○	○	○
8.5 Rumble Strip or Chatter Bar	○	○	○	○	○
8.6 Painted	○	○	○	○	○
8.7 Bi-directional Turn Lanes	○	○	○	○	○
8.8 Mountable Median	○	○	○	○	○

9- Effect of **Traffic Control Devices** on Reducing Work Zone Crashes

	Least Effective 1	2	Medium Effect 3	4	Most Effective 5
9.1 Message Boards	○	○	○	○	○
9.2 Speed Displays	○	○	○	○	○
9.3 Flagger	○	○	○	○	○
9.4 Truck Mounted Attenuators (TMAs)	○	○	○	○	○
9.5 Police Presence	○	○	○	○	○
9.6 Automated Photo Enforcement	○	○	○	○	○
9.7 Arrow Boards	○	○	○	○	○
9.8 Channelization Devices	○	○	○	○	○

10- Risk Level of **Vision Obstructions** on Crash Occurrence

	Lowest Risk 1	2	Medium Risk 3	4	Highest Risk 5
10.1 Trees	○	○	○	○	○
10.2 Signs	○	○	○	○	○
10.3 Construction Equipment	○	○	○	○	○
10.4 Glare from Sun	○	○	○	○	○
10.5 Glare from Headlights	○	○	○	○	○
10.6 Glare from Nighttime Work Zones	○	○	○	○	○
10.7 Horizontal or Vertical Curves	○	○	○	○	○
10.8 Temporary Concrete Barriers	○	○	○	○	○

11-Risk Level of **Work Zone Speed Limit** on Crash Occurrence

	Lowest Risk 1	2	Medium Risk 3	4	Highest Risk 5
11.1 35 mph	○	○	○	○	○
11.2 45 mph	○	○	○	○	○
11.3 55 mph	○	○	○	○	○
11.4 Advisory Speed Reduction Only	○	○	○	○	○
11.5 No Work Zone Speed Reduction	○	○	○	○	○

Comments

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12- Please evaluate from 1 to 5, from lesser to higher importance, each of the following **Work Zone Parameters** according to its influence on the safety of work zone

	Least Importance 1	2	3	4	Highest Importance 5
1- Work Zone Layout	○	○	○	○	○
2- Work Zone Hours	○	○	○	○	○
3- Work Zone Duration	○	○	○	○	○
4- Work Zone Type	○	○	○	○	○
5- Right-side/Median Shoulder	○	○	○	○	○
6- Route Prefix	○	○	○	○	○
7- Traffic Lane Width (Lane Constriction)	○	○	○	○	○
8- Median Type	○	○	○	○	○
9- Traffic Control Devices	○	○	○	○	○
10- Vision Obstructions	○	○	○	○	○
11- Work Zone Speed Limit	○	○	○	○	○

Comments

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1. What are your recommendations to improve work zone layouts to minimize work zone crashes?

2. What types of innovative work zone or traffic control devices do you recommend to minimize work zone crashes? How would these devices enhance IDOT's work zone current practices? Please explain.

3. If temporary rumble strips (6~8 strips/set) can be used prior to or at the edge of work zones, where do you recommend them to be placed within the work zone layout? Please explain why?

Click to Go Back | Finished? Submit your Survey

Thank you for taking our survey. Your response is very important to us.

APPENDIX C

RESPONDENTS' RECOMMENDATIONS TO IMPROVE WORK ZONE LAYOUT

What are your recommendations to improve work zone layouts to minimize work zone crashes?

DATA	
CODE	**VALUE**
61780347	Message Boards and 3-5 and 1 mile distances before WZ are the best. Minimize signage.
61785198	Eliminate the use of mobile operation standards on highways with speed limits of >55mph or high ADTs. Utilize more road closures on bridge work, as the workers will not be subjected to moving traffic and road obstruction time will be reduced.
61784396	#1 Consistency from site to site based on road use (interstate, urban highway, rural highway, etc). #2 Strict enforcement of traffic control deficiency penalty for improperly maintained and placed workzone traffic control devices.
61793492	USE CRASH ATTNUATOR TRUCKS
61795704	Less stage construction and more crossovers to seperate traffic from construction
61802831	A realistic approach to what the actual field conditions are. Many times the Standards are thrown into a set of plans and they just don't fit or work in the real world, I have never seen any standard fit everywhere. There needs to be in our policies the ability for Professional Engineers to make Engineering decisions to address actual field conditions without the threat of liability because a standard wasn't followed to the letter of the law. Perhaps we should call them Highway Guidlines for Traffic Control and remove the word 'Standard' so slight adjustments can be made in the actual field placement without teh concern of not meeting the exact disatnces stated on many standatrds. The standards as written generally don't allow for any deviation and are for an ideal world.
61815186	Don't overload the area with signs - too many and they all get overlooked.
61873235	trim vegitation to allow better sight distance of early warning/work zone signage (this area is not considered to be in the limits of the work zone, so no work is allowed because it is out side the scope/area of work)

DATA	
CODE	VALUE
61872239	For interstates, provide 2 lanes thru work zones whenever possible or use conc. barrier and place traffic head to head on one side while giving us the other side to work on.
61872623	Use the correct taper length as a minimum and be sure the taper is a solid row of channel devices. Be sure that it is inspected and maintained. Use arrow boards in the appropriate locations relative to the tapers. Flaggers also help when they hold their paddles and communicate to the drivers appropriately when they drive by - if necessary.
61877223	Outlaw cell phone use.
61877252	More personel to watch each other backs. Can get layout done faster with more people. We need to hire more technicians.
61878972	1. More total closings. 2. Minimise work after dark.
61878787	I feel that our current practices are effective.
61875190	Use as much advanced warning as possible.
61880350	More protection for flaggers--maybe some more advance warning other than the 3 signs now required
61877536	Make the traveling public pay more attention to driving and more work zone examples/visits during driving education classes with young and old drivers.
61881378	Utilize traffic detours during 3R projects that estimate more than 6 months of construction time. This will save lots of money on traffic control staging, vastly improve the quality of the finished product by not having to cut the work up in pieces for staging, and put the traffic on a safe and unobstructed route to travel. This will only cost the motorists time and fuel, but may get two year projects done in one year and one year projects done in a few months.
61890159	More police presence. Devices that show vehicles speeds to drivers.

DATA	
CODE	VALUE
61889345	Increased police assistance would greatly reduce the frequency of work zone crashes. Police assistance in not only needed on the interstate system but would also be welcome on secondary rural highways. Another help would be a speed reduction for two lane highways as well as for interstate. flagges would be more effective on two lane roadways if contractor were required to use portable flagger signals instead of it being optional.
61890675	I've not seen a crash in the work zones. However, I've seen some crazy behavior from motorists in work zones.
61877731	Closing roads to traffic is the only way to make work zones safe for the motorists and the workers. Traffic should be detoured. We are always told that is too much inconvenience to the "travelling public" Being dead or paralyzed from a work zone crash is considerably more inconvenient in my opinion, whether it is the motorist or the worker injured or killed is not the point. People should not be driving in my workspace.
61877916	Not all standards fall within the parameters of work site. Often common sense should dictate some revisions, but everybody is afraid to reduce lenghts for minimum distances or something for fear of law suits. (ie. especially around various interchanges closely spaced).
61892083	Have police officers there when laying out traffic control
61899700	Incorporate more detail in the stage constructions plans with more room with lane width and lengthth.
61903574	Simplify everything. Too much information is confusing and distracting.
61927117	early warning information
61930108	I think using more detours would reduce work zone crashes. If we eliminate traffic alltogether in our work zones, there won't be crashes.
61928350	Tighter spacing of traffic Control devices and reduced speed limits along with police enforcement.

DATA	
CODE	VALUE
61932639	Enforce work zone plan, and penalize contractors who fail to provide directed traffic control or correct deficient traffic control
61930281	Some contracts have too many advance signs, travelling public tends to ignore signs if there are every 500'. Maybe less signs that are bigger and/or flashing. Police on site help slow traffic down better than any sign we put up.
61934175	Speed Bumps
61932262	More Barricades, barrier walls, pavement marking and signs.
61944188	Most of the time layout work is completed without the use of traffic control. This is very hazardous to the inspectors completing the layout. Traffic Control signage, TMA's, flaggers, police enforcement or lane closures would greatly minimize work zone crashes it this area.
61950655	More Police (Hirebacks/Gabz).
62009896	Have a construction vehicle follow the work crew on foot
62012523	Make sure the layout is done according to the specifications. Check consultant plans more thoroughly as sometimes the traffic control does not agree with specifications.
62013148	PUT A BIGGER SIGN FOR SPEED REDUCTION AHEAD
62014087	Given plenty of advance warning to traveling public and enforce safe work zone layout. Safer takes longer and costs more money!
62013311	TMA LANE CLOSURES FOR INTERSTATE & EXPRESSWAYS FOR 2 WEEKS BEFORE CONSTRUCTION BEGINS.
62012760	Avoid beginning lane closures near or after a crest in a hill, avoid closing a lane in a horizontal curve,

DATA	
CODE	VALUE
62018956	More photo enforecement and more police presence
62018159	Ensure the appropriate equipment and personnel are available.
62017613	If Centerline layout is needed in open traffic, that enough flagging, And signage be provided.
62019124	To have the plans accurately show the layout and to match field conditions, rather than going by a standard.
62022660	Road Construction Ahead 5 Miles signs installed in addition to R.C.A. 3 Miles Ahead.
62025740	Police presence in work zone when doing layout and set-up of work zone.
62072864	Adequate transitions, multiple warning signs, advanced notice of work using message boards
62157048	The use of more state police in construction work zones seems to be the only way to slow traffic down.
62157681	It's not the layout, its the ignorance of the traveling public that causes most of the accidents.
62155549	No ideas above what we already do.
62156691	Contractor needs to have traffic control set up 2 weeks before starting the job so the state personel can do layout under traffic control.
62156192	TMA for all layout.
62158979	lengthen tapers
62155883	I feel that the best thing that would help minimize wz crashes would be

DATA	
CODE	VALUE
	to delineate the work zone better, not only before it, but throughout it. I have gone through some work zones when there where no cars infront of me and had to "guess" on where to go because of poor delineation.
62156256	If feasible, setting up traffic control for layout purposes would be nice.
62156327	The presence of law enforcement along with signing stating the fines always gets the attention of the traveling public to be aware of the work zone.
62158943	construction trucks should be more equiped like our maintenance lead workerks.Maybe a flagger and day time layout also on Sunday less traffic.
62166743	Its not always a need to improve the layout so much as the need to have the layout set up properly.
62168301	Contractors need to send out bigger crews so that there is protection for the workers laying out and placing the devices. Flaggers or arrow boards.
62172752	Police presence
62173509	To really enforce the Scott's Law even truck drivers do not pay attention to it and if more people were held accountable and or even made aware of the Law. So many people have no idea that it exists.
62169665	Layout the Traffic Control to best suit the needs of the area effected by the project. Consider the work to take place and how the contractor will complete the work while providing a safe work environment for the construction crew and the motoring public. We need to inform/provide a safe work zone and traffic control for the motoring public - since we are at their mercy.
62174220	Mandatory that traffic control engineer or technician layout and or verify that traffic control is layed out correctly.
62173354	Installation of signs informing public of upcoming work, 1 to 2 weeks

DATA	
CODE	VALUE
	prior to work starting.
62175325	The most frequent crashes are rear end crashes due to stopped or slowed vehicles. Reducing speed limits prior to work zones, additional advanced warning signs ("Stopped Traffic Ahead" with flashers), and a thorough review of striping and patching traffic control issues could reduce frequency.
62200740	Speed limit enforcement Work zones and/or travel lanes layout
62207776	Make traffic control signing as easy as possible to help motorists understand exactly what they need to do and where to go.
62183692	Use temporary barriers when needed, try to schedule police enforcement where possible, use advance signing in moderation to avoid a barrage of orange, ensure channelization is highly visible day or night, reflectivity is preferable to battery power.
62206578	Lots of times I have seen signs for flagger ahead or lane closed ahead/merge left or right, but when you get ahead there is no flagger or closed lane or any merging. After a while people will just ignore the signs and drive normally without any caution.
62454742	Work zone layouts should be tailored to each situation. The dimensions given are a guide and should be adjusted as needed in the field to make for the safest possible traffic control setup.
62457036	Lower the work zone speed limits.
62456883	I think some of the traffic control standards are pretty generic. When there are sideroads and offramps, a case by case design should be utilized.
62462714	Advance warning, larger and more visible signage, message boards, rumble strips etc... and reduction in speed within construction zones.
62479991	Work zone standards should be adjusted for the roadway geometry (horizontal and vertical curves) and the terrain (trees or tall grass). The

DATA	
CODE	VALUE
	channelization devices should be properly spaced and the signs properly placed in advance of the lane closure or work zone as to give the motorists adequate time to merge or make them aware of a hazard. Also, the condition and cleanliness of the devices should inspected as well as the work zone checked at night for the readability of the signs.
62492918	Allow interstate entrance ramps to be closed for short duration during paving or patching operations.
62591104	reduce speeds on two lane roads. Traffic barriers on 4 lane +
62608638	Slower speed limits, $375 fine signs
62605398	I have no recommendations.
62616459	Simplify the layouts for the motoring public. Some of the layouts are too complex and are difficult to follow at times
62728359	More CMS
62747775	Make sure there is plenty of advanced notice(signs, message boards)
62742791	Maybe we could add flashing lights on the Road Construction Ahead Signs to alert motorists even more that they are approaching a construction zone.
62784728	Try to let in advance the newspapers and Tv what is going to happen in the area.

APPENDIX D

RESPONDENTS' RECOMMENDATIONS TO UTILIZE INNOVATIVE WORK ZONE AND TRAFFIC CONTROL DEVICES WITHIN WORK ZONES

What types of innovative work zone or traffic control devices do you recommend to minimize work zone crashes? How would these devices enhance IDOT’s work zone current practices? Please explain.

DATA	
CODE	VALUE
61782850	rumble strips
61780347	Drone Trooper cars even with "dummy cops" in the seat. Tickets dont slow cars down. But a sqaud car in the work zone does.
61793492	POLICE PATROL! TRAVELING PUBLIC ONLY SEEMS TO RESPOND TO POLICE PRESENCE. SIGNS ARE IGNORED MOST OF THE TIME. PEOPLE DRIVE BY SIGNS ALL OF THE TIME AND CAN'T EVEN TELL YOU WHAT THEY SAID!
61795704	I'm not sure what more can be done to increase awareness in the work zones. i feel that most of the accidents are the result of driver error as opposed to a problem in the layout of our work zone.
61802831	With the new reflective sheeting that is out there today, i don't know why we need lights on any of the signs, drums, or panels. The reflectivity today is so much brighter than yesteryear, they actually are brighter than lights. This will also reduce the number of batteries that are landfilled each year and should reduce litigation in the case of an accident because a light was out. The use of properly placed message boards with correct information should be encouraged. The issue here is on many rural roadways in Illinois, there is no place to place them out of the travel lanes due to narrow ROW's and shouldrs. The IL DOT needs to embrace a program of actually reconstructing our roadways versus just resurfacing them time after time.
61870964	Place a flashing light on stop/go paddle. This would make the flagger more visible. Also, the flagger should have a "boat horn" to warn workers when there is an emergency.
61873235	speed limit advisory signs with a digital speed display that shows oncoming traffic their actual speed
61872623	No comment

DATA	
CODE	VALUE
61877223	concrete barriers.
61877252	Better striping on bridge work and after resurfacing projects. Many times it's hard to see when it's raining. Harsher fines on contractors if they leave the jobsite and their traffic control is a mess. Many times I have fixed it on my own time because no one was still around.
61875190	Use more message boards, and radar signs telling people if they are speeding.
61879387	A speed trailer displaying the motorists speed is an effective device. It gets vehicles to slow down making the work zone a safer place to work and prevents high speed accidents.
61880350	More police writing tickets
61877536	The use of more drums than cones. Drums are bigger which can allow the traveling public to see where they need to drive. More lights or bigger light bars on vehicles (including contractors vehicles) within the work zone.
61881378	Offering a suggested route on a website/message board/radio/media outlet to reduce traffic volume. Photo enforcement of speed limits, will reduce motorists speed for fear of financial cost. The slower the traffic the fewer the crashes.
61889345	Portable flagges signals would greatly increase the flagges visability and effectiveness in the work zone. Enforced 45 mph speed limits on all roadways marked 55 and over would also reduce crash occurences because motorists would have more time to react.
61890675	TMA's seem to work very well for moving operations.
61877731	POLICE PRESENCE; if traffic is permitted in our workzones the only measure that I have seen having any impact on driver behaviour is an officer in a marked police car with lights on at the start of a workzone and a second officer actively writing tickets thru the workzone. Perhaps prior to receiving a driver's license, and on each renewal applicants should have to stand in a workzone next to an open lane while traffic

DATA	
CODE	VALUE
	goes by at interstate speed for half an hour or so, to better appreciate the danger they are creating by acting like there is no work zone.
61877916	Use of mini cones/barrels there is a type used in Iowa that is called Grabber Cones, by Lakeside Plastics. They would work great in Urban areas with narrow lanes and allow a light to be mounted to the top of it. They are used in Iowa and Indiana, but are not allowed in Illinois, why not?????? I have used them for one urban job with 12' mulitlane pavement with curb & gutter along the edges. During paving they only took up about 1.5' of roadway width outside of the 1' needed for the paving ski in the open traffic lane and would allow appox. 11' traffic lane when paving. Per spec a 10' minimum lane is required on multilane roadway but paving urban multilanes requries traffic control devices to placed 1' to 1.5' beyond the paving joint on lane line and then the width of the device reduces the open traffic lane even more. So Grabbers only have a 2' bottom and about 12" diameter cone starting in the middle and narrowing up to about 6". Still providing the minimum 10' lane. In addition, why are lights required on Traffic Ctrl devices in urban areas with overhead street lights along the roadway. The lights barely light up and the overhead street lights provide amble ambient light. This would save millions of batteries and the enviroment not to mention reduce the risk of a flying object (heavy battery/light) when devices are hit.
61892083	Letting us use the grabber cones....they are very effective and small when working in narrow areas....but district traffic engineer won't approve them even though other states use them all the time.
61897475	see other coments on Grabber Cones.
61899700	barrier wall, crash wall,
61903574	None come to mind at this time.
61927117	enforce the use of flaggers. People tend to slow down alot more when an actual person is standing there holding the "slow" sign
61926352	More advanced message boards.
61928350	Arrowcades could be used more. Along with the use of arrowcades comes more responsibility to make sure they are facing the right

DATA	
CODE	VALUE
	direction. If people are not told which way they should go....they like to find their own route and it is usually not the right route.
61930281	Message boards are very nice. The Department should also look at eliminate the use of the green vests in rural areas - blend the worker into the background of corn fields etc.... the bright orange shirt works much better in this scenerio. Also, see answer to question #1.
61934175	More Message Boards and Arrow boards
61944188	Red and blue lights with an officer writing tickets. Police enforcement could be utilized at work zone locations where workers are present. The officer could detect the speed of the oncoming vehicles and radio ahead to the another officer where they could direct the motorist to the shoulder where a citation can be issued. The more tickets the officers write, the quicker the traveling public will react to the work zone situations. This manner would be effective because motorists would see how serious it is to speed through work zones. This would enhance IDOT's work zone practice effectively because motorists would pay attention in the construction zones therefore reducing crashes.
61950655	Inform the traveling public how long a work zone is. Such as Road Construction Ahead Next 6 Miles. I think people who read signs may be more understanding with regards on how alert they are in work zones. This is helpful to keep people from merging into a taper with increased speed.
62013148	ARROWCADES ON THE INTERSTATE DO NOT WORK THEY CANNOT TAKE THE SEMI'S
62014087	Enforce work zones are set up more consistently and maintained in a timely manner. When traveling public recognizes a pattern they will be more likely to know what to expect.
62013311	MORE EFFECTIVE & EFFICIENT USE OF STATE POLICE. TRAFFIC ALWAYS SLOWS DOWN FOR RED & BLUE LIGHTS. ASSIGN AN OFFICER TO JOBS ON INTERSTATE & EXPRESSWAYS FOR ATLEAST A COUPLE OF DAYS A WEEK.
62012760	When there is a sight distance issue involved and when traffic is being

DATA	
CODE	VALUE
	stopped, I like to add a "Be Prepared to Stop" sign to the other advance signs. I feel that a "Flagger" sign does not adequately get the message accross that traffic may be stopped ahead, but when the sign says Be Prepared to Stop, then I believe people are more likely to heed the warning. In cases of extremely limited sight distances and when traffic is being stopped, I like to add an additional flagger ahead of the traffic backup. This flagger holds a "Slow" sign and, on a two lane road, it is also necessary to completely cover the Stop portion of the sign. My opinion of all this is that not all people take seriously the advance warning signs, but more people will give a greater weight to a flagger that is showing a slow sign and is also waving them down to slow.
62018159	Type III Barricades. Do more work under closed roads.
62017613	The use of more arrowe boards and channeling devices. I think that if more were added this may help?
62014741	Photo Speed Indicators appear to slow vehicles down to the Work Zone speed limits
62019124	Police presence, radar emitting vehicles and speed displays really slow down vehicles. The enhance them because they are not currently part of the contract standards.
62022660	Provide speed indicators for the motorists current speed.
62072864	Having the maximum number of police hours seems get drivers to slow down the best.
62154443	In stead of battery operated lights for nighttime traffic control, I suggest reflective panels. There is almost no maintencne of variance in brightness. Very effective
62157681	constant police presence
62155549	I don't think that they are too innovative, but we should be using reflective tape in the place of lights on barrels for nighttime closures. These devices would enhance IDOT's current practices because they are brighter and consistent.

DATA	
CODE	VALUE
62156691	Have more cops patroling work zones. That is the only thing that slows down traffic to prevent accidents.
62156192	State police. The presence of a state police officer with the threat of paying $375 seems to be the most affective control for the safety of the work zone.
62158979	stage construction - make both directions red until trafic approaches
62155883	I had to go through a work zone on the interstate that was up for about 2-3 months on my way home last year. It had a flashing speed limit sign at the beginning of it by the 55mph signs. i was very surprised by the number of vehicles I saw really slow down when they went by it. I was really impressed by how much attention it got. Near the end of the project, I did notice that not as many vehicles were slowing down when passing it. I think that this would be a good tc device to use, but I also feel that it should be moved throughout the wz, if it is a lengthly wz.
62156256	I would like the addition of a red/white/blue strobe light on our vehicles. The most effective device I have seen to slow down vehicles is a police car. Another option would be to allow the police to use IDOT vehicles to clock and write people speeding tickets.
62156327	Message Boards prior to the work zone but also within the work zone explaining possible hazards of the construction taking place. The placement of speed reduction signs placed throughout the workzone with the presence of law enforcement. It seems that the traveling public might pay greater attention to the workzone operations if a fine might be assessed. In some 10 mile paving jobs there might be 1 or more operations taking place and the public thinks that once through 1 operation, they will not be aware a second or third operation might be taking place. The continued signing of workers, trucks and paving equipment are present in the workzone.
62158943	Interstate work zones 3 miles max, this would allow the contactors to get in and get out.
62166743	As this time I do not have any recomendations.
62172752	Cocrete barriers, see previous comments

DATA	
CODE	VALUE
62173509	I feel there is so much signage and cones that people become numb to it. We need less but bright and flashing to catch the eye of the driver.
62170787	Give alternate route information to the motorists via sign or changable message. This should relieve congestion and impatiance. Motorists need more work zone education to recognize they cannot afford to be distracted.
62169665	Motorcycle patrols were very effective on the interstates. If we could design a safe area for the motorcycle patrol/patrol cars to enter and exit the project within the construction stages. (While on I-57 in Mt. Vernon we had Concrete Barriers setup NB & SB with access at the ends for contractor's trucks and state police. These areas were WELL received by the motorcycle patrols - they would park behind the barriers while shooting their radar - Very Safe.)
62174220	There are stop signs at some intersections that have lights on the peimeter of the signs. If the same thing can be done with stop/slow paddles that are used by flaggers the work zone safety would be greatly enhanced. Too often the flagger and paddle blend into the back ground. Lights on paddles would make the flagger stand out and traffic would slow down more quickly and approach the work area with more caution.
62175325	"Stopped Traffic Ahead" with flashers could help in urban situations where message boards are too large.
62207776	Changeable message signs to help inform the drivers of where to go. Camara's could be used to view different construction sites and see what type of accidents are occuring and the data could be studied to prevent future accidents in similar types of construction zones.
62183692	Photo enforcement of speeding violations could slow traffic down, I have not seen this technology in our district. A mobile or more easily manueverable temporary barrier would allow its use in more applications and may precipitate a reduction in prices, allowing designers to specify barrier more frequently.
62206578	The TCD's currently being used are very effective if used properly: Keep them clean so they can be seen 24/7 and more importantly if there is a sign instructing drivers to merge left or right due to lane closure then have the lane closed.

DATA	
CODE	VALUE
62454742	State Police Hirebacks and photo enforcement seems to do the best as far as slowing the traveling public in our work zone to a more manageable speed.
62457036	More use of temp rumble strips and speed trailers. The rumble strips help keep the drivers attention that something is approaching and the speed trailers are a great visual tool to let the driver be aware of how fast they are going.
62456883	From previous experience, message boards really inform the public on what to expect. Since work zones change daily, it is good to inform the motoring public of changing conditions.
62462714	The use of message boards. Signage is easily overlooked by motorists. The use of message boards on all projects does a better job at increasing awareness and informing motorists of changing roadway conditions within a work zone.
62492918	Use truck mounted mesage boards on interstate projects
62591104	Movable barriers. They would protect the workers better
62605398	Depending on the route, ADT, traffic type and work zone(allowable area) the traffic control devices may vary. In many cases an attenuator system may be need for construction activities. However, the attenuator will vary depending on the allowable work zone. The traffic control devices that our used by IDOT today, I might say are very good. What I would very much like to see change are the spacing of the barricades, drums, or cones into a tighter configuration. Especially on highway construction.
62616459	Road Closed Signs!!
62747775	Pavement marking and rumble strips in advance of the work zone get peoples attention before it is too late.
62742791	See answer to #1. Maybe IDOT could begin using a narrower barrel or some type of narrow panel to channelize traffic in lane closures. The current barrels used are to big in areas where the lanes are narrower

DATA	
CODE	VALUE
	than 12 ft in width. Also, IDOT needs to do a better job in issuing permits to wideloads. For some reason the patching contracts are not known about and/or are not considered when issuing these permits. Last year a wideload was going to go thru my project when I had open holes during the patching operations and guardrail driectly across from those patches along the shoulder. There was no way possible that a wideload would be able to make it through our work zone.
63164638	More state police hire/backs on interstate routes.
63171829	Automated Photo Enforcement for temporary bridge traffic signals.

APPENDIX E

RESPONDENTS' RECOMMENDATIONS TO PLACE TEMPORARY RUMBLE STRIPS WITHIN WORK ZONES

If temporary rumble strips (6~8) strips/set) can be used prior to or at the edge of work zones, where do you recommend them to be placed within the work zone layout? Please explain why.

DATA	
CODE	VALUE
61782850	by speed reduction signing
61780347	They should be located at the signs that indicate the reduced speed limits.
61785198	Placed in parallel with the work zone speed limit signs, signaling to the motorist there is a hazard ahead.
61784396	Yes for sight distance issues: if closure is after or within a vertical or horizontal obstruction, they should be utilized in the lane to be closed 1/2 to 1/4 mile before lane change taper.
61793492	NO, PEOPLE SEEM TO IGNORE THEM DURING LONG DURATIONS OF CONSTRUCTION.
61795704	They need to be as close to the work as possible. I feel that one problem with our set-ups on multi-lane projects is the distance between speed signs and the work. If a driver slows down but does now see any work in the next 1000 yds. they will tend to speed up. Maybe the rumble strips could be used as a temporary set-up only when workers are present.
61802831	I don't think they should just randomly be placed 'prior to or at the edge of work zones' on a random bases. On a staged project how are these removed if traffic has to cross them on succedding stages? While I like rumble stripes as a way to get the mototist attention, I think great care and planning has to be taken before they are part of the traffic control plan to assure no future conflicts with the live lanes of traffic. It may be such that the use of rumble stripes are not contiguous/consistent and they could be more confusing then helpful.
61870964	I believe we only need temp rumble strips where they are currently used for stopping conditions. The biggest problem with temp rumble strips is the maintenance of them.

DATA	
CODE	VALUE
61872239	place in the lanes of traffic just after the first road const ahead sign to alert traffic to upcoming changes.
61872623	Suggest a set to be placed at 200' and then at 500' bdfore the work zone.
61877252	Rumble strips are fine in the locations they have in the standards.
61878972	Stacked along the fence, They are of little use and create trash to pick up.
61878787	with the signs before the job limits to alert the motorists that construction is ahead.
61875190	I think placing them in advance of the warning signs so that people will read the signs would be worth a try.
61879387	I agree with the current standard on the placement of the rumble strips. I would rather see flashing lights as a visual than rumble strips. Temporary rumble strips are hard to keep down.
61880350	I like them a little ahead of thr RCAs, one in the midddle and one fairly close to signals for a last ditch attempt to wake people up.
61877536	Possibly at tapers to mark non-driving areas, but these also could make the drivers take their eyes off the road - thinking they hit something.
61881378	They only work if they are in the right places at the right times. If the contractor is slow in removing them or no work is going on immediatly in front of the traffic that hits the rumble strip, traffic will ignore the rumble warning. THe same goes for all advisory signs and devices.
61890159	Prior to any major operation. Make them temporary and easy to move from one location to another.
61889345	use of temporary rumble strips can only be practical at stationary long term operations. they should be placed prior to the flagger or temporary

DATA	
CODE	VALUE
	traffi control device.
61890675	Placed about 1500' out due to lack of concentration of the average motorist. It doesn't seem to matter how many signs you place ahead. I think peolpe have short term memory issues or distracted by something else.
61877731	I cannot recommend any placement as I have never seen them used to determine what impact they have on driver behaviour. My intuition, based on years of being in work zones, is that a driver will lift their foot from the accelerator while passing over rumble strips but then return to speed as soon as the noise stops.
61877916	On the tapers for Bridge Construction projects. Place them along the edge of the outside lane that tapers from the EOP to the outside edge of the construction traffic lane across the bridge usually adjacent to the parapet of the bridge. Only need a few to help guide them to the edge in the taper area only. In additon, along long duration weaves along the weaves painted edge lines, they would only need to be 2 or 3' long spaced every 50' or so as you weave traffic. Especially on Interstates and at night where drivers get a little tired. Might wake them up before they hit TC devices or blow right through the weave completely.
61892083	before the layout to warn people they are coming up to a construction zone
61899700	Temporary rumble strips do not work. The traveling public will avoid and drive into the other lane.
61903574	Only use them in a traffic stopping situation, such as temporary signals. Any other use would more likely cause a panic.
61927117	I would place them before any tapers, to let the motoring public know that there is a change coming up.
61926352	1000-2000 feet. Plenty of advanced notice, but not too close to the work area.
61928350	Rumble strips could be a useful practice. The only questions I have

DATA	
CODE	VALUE
	about rumble strips would be as follows: 1) size - if you get on the other side of the rumble strip and your tire doesnt hit it....then it is useless. 2) When drivers hit rumble strips...they may have a tendency to jerk the wheel back. Does this create a more hazardous condition?
61930281	Prior to lane restriction/closure sign, work zone speed limit sign, and the flagger sign. These would help to get the drivers attention and possibly have them read the signs and what to look for ahead.
61934175	Two of them. One well prior to job and one just before work.
61932262	At the begining of the work zone at the edge.
61934201	Unless you're on a blind hill or curve approaching a work zone. I am not a fan of rumble strips. I believe they just act as a deterrent of the motorist.
61944188	If these were to be used they would have to be removed at the end of the days work. If they were to be placed they should be approximately 1000' before the flagging operation. They rumble strips should be moved to keep up with the operation.
61950655	One thousand feet in front of the Lane Closed 1 mile sign.
62012523	500 ft before the barrel taper. This will alert the driver that a lane change or traffic signal is ahead, but will not warn to early as they will forget.
62013148	AT THE REDUCED SPEED OR ONE LANE ROAD AHEAD SIGNS -SO IF THEY ARE SLEEPING IT WILL WAKE THEM UP IN TIME TO SLOW DOWN OR STOP
62014087	I do not think rumble strips will make work zones safer.
62013311	500' BEFORE ALL 701400's SIGNS. RUMBLE-RCA, RUMBLE-1 MILE, RUMBLE-MERGE, RUMBLE-ARROWBOARD

DATA	
CODE	VALUE
62012760	To wake up the day dreamers, I would recommend them be placed starting at 1000' ahead of a lane closure taper.
62018956	Place prior to the advance warning signs. When a car drive over the rumble strip it will have time to read the signs.
62018159	Yes. On roads where drivers aren't expecting slow or stopped traffic.
62017613	Placed 100' before work zones, or were men are working.
62018444	They should be utilized with the work zone speed limit signs to help drivers slow down. The only problem with using these devices are noise complaints from residents and property owners.
62014916	on new or temporary traffic signals &/or stop signs. Because, they are new (different) devices that the public is not used to.
62014741	Prior to the work zone to emphasize the need for the driver to follow the posted work zone speed limit
62019124	Located prior to traffic merging or entering the highway within the work zone. To help slow down traffic and to enhance the signing.
62022660	At beginning of Traffic Control and just prior to long-term lane closures.
62072864	About 300 ft in advance of the warning signs. This alerts drivers to read the signs.
62154443	I suggest they begin at the Road Construction 1 mile sign, another set at the 1/2 mile and a final set once the taper for the lane reduction ends.
62157681	500' prior to flagger
62155549	I think that they should be placed prior to the taper into the lane closure in order to alert the motorist that something is about to change.

DATA	
CODE	VALUE
62156691	Have them starting 500 feet before entering the work zone so motorists know to slow down.
62156192	Next to the flagger.
62158979	in advance of approach to job, to get attention
62155883	I would recommend that they be used in advace of the work zone, where we have the road closed ahead, 1 mi. sign. This seems to be the start of all the "action" in the work zone, so it would be a good attention grabber (One would hope that they would already be paying attention).
62156256	I would place them somewhere in the vicinity of the "Flagger" signs, approximately 500' prior to the flagger.
62156327	Rumble strips are only as good as the continued maintenance to keep them effective. Advanced signing should have high intensity mutiple flashing lights.
62158943	It depends on were the activity is, if you are on the interstate and working both bounds then I would place them on the passing lane & shoulder side, if you are working on a lane with slope work than I would place them on the driving lane & shoulder next to the work area.This might be a the last warning to the motorest before hitting a worker.
62166743	At this time I do not have a reccomendation.
62168301	They should be by the speed reduction signs to warn people to slow down. If work is to be done at night it would be nice to have them at the advanced arrow board locations. Most people don't get over or slow down until they absolutely have to. If they were placed in advance of the closure maybe it would get people to pay more attention to what is coming up.
62173509	500' from the work zone to give the driver time to recover to the roadway.
62170787	Within the lane reduction and edge of work zone. This will alert drivers

DATA	
CODE	VALUE
	who are veering into the work zone.
62169665	Temp rumble strips may bring other problems to big projects. However, on some bridge projects they may increase safety. The designer will need to think them through. (ie. Temp raised reflective pavt markers vs Snow Plows; Channellizing; Install & Removal.) Easy to install and effective but problems with removal / relocation - consider types and process.
62174220	The same way they are used now.
62173354	Place them at the advance warning signs(road construction ahead, one lane road ahead, flagger, etc.). This would get the attention of drivers that do not pay attention to the signs.
62175325	The location should be 500 feet past the farthest estimated queue of stopped or slowed vehicles for work zones where stopped or significantly slowed traffic is expected. A traffic simulation program may be necessary to determine average queuing.
62200740	I will recommend using them prior the work zone to provide additional warning to motorist
62207776	I would think this could cause rear end accidents by people slowing down before they go over them. If absolutly necessary I would put one set ahead of where the traffic back up would be expected to be during rush hour and another set several houndred feet before the start of the work zone.
62183692	Not far from planned work, to avoid motorists passing them and speeding up again.
62206578	All the drivers hate rumble strips. It is annoying and wears out the tires, but they work. I would have them placed prior to entering a work zone, because people will try to avoid them if they are along the edge of the work zone and might cause an accident.
62454742	I could only see these working on stationary setups. As a lane begins to merge out they could be placed in the lane that is ending to emphasize

DATA	
CODE	VALUE
	that the lane in ending as the taper is transitioning in the closed lane.
62457036	I think the you should use 2 sets, one at the first set of signs for the approaching project and another right before the taper for the closed lane. I think that they get the attention of the driver better than just reading the approaching signs.
62456883	I think the best placement is in a location that alerts the motorist that there could be a possibility of stopping ahead or some type of danger.
62462714	Prior to advance work zone signage. Motorist simpily don't notice or pay attention to advance warning signage. If rumble strips were placed at these locations, this may enhance the overall awareness of an uncoming construction zone.
62474600	Temporary signals used on 2 lane staged bridge construction with sight distance problems - 3 sets in advance of signals
62591104	Depends on the type of construciton. 4 lane should be throughout the construction limits. 2 lane before the flaggers, but they move daily so this would be almost imposible.
62608638	1000' upstream of where people are working
62605398	I recommend that rumble strips should be place at least 1000ft from the work zone. Also, this depends on the speed limit of the roadway and the allowable time for a motorists to stop.
62616459	No rumble strips!!! that would only frustrate and already nervous driver!
62747775	I think they should be placed near the first sign so drivers realize they are entering a construction zone, and just before any directional signs(merge, chsnge lanes, etc.) so drivers learn they need to take action.
62742791	The first couple of sets should be set directly across from the Road Construction Ahead sign and the rest could be placed 500ft from the beginning of the work zone.

DATA	
CODE	VALUE
63152749	One set in advance of first waring signs so motorists will be alerted to hazards and look for signs, second set at the start of the work zone to alert motorists who have missed the warning signs.
63171829	200' +/- in advance of warning signs

APPENDIX F

RUMBLE STRIPS DATA

Table F1 Sound Measurements of Rumble Strips Prior to Work Zones (8 strips/set)

Reading Number	Pattern	Vehicle Type	Rumble Strip Type	Speed Limit (mbh)	Spacing (inch)	Sound Readings		
						Ambient	Rumble	Effect (dBA)
1	8strips/set	Sedan	ATM	50	12	70.14	80.4	10.26
2					24	70.14	84.3	14.16
3					36	70.14	80.5	10.36
4				40	12	68.24	80.7	12.46
5					24	68.24	80	11.76
6					36	68.24	77.3	9.06
7				30	12	65.01	78.6	13.59
8					24	65.01	77.3	12.29
9					36	65.01	74.5	9.49
10			Swarco	50	12	70.14	84.9	14.76
11					24	70.14	84.4	14.26
12					36	70.14	83.3	13.16
13				40	12	68.24	80.3	12.06
14					24	68.24	80.8	12.56
15					36	68.24	82.7	14.46
16				30	12	65.01	78.5	13.49
17					24	65.01	77.2	12.19
18					36	65.01	77.2	12.19
19			Road Quake	50	36	70.14	83.5	13.36
20				40	36	68.24	82.7	14.46
21				30	36	65.01	87.7	22.69
22	8strips/set	Van	ATM	50	12	67.98	80.6	12.62
23					24	67.98	81.4	13.42
24					36	67.98	80.6	12.62
25				40	12	63.91	82.6	18.69
26					24	63.91	77.2	13.29
27					36	63.91	83.3	19.39
28				30	12	60.58	72.6	12.02
29					24	60.58	79.9	19.32
30					36	60.58	73.3	12.72
31			Swarco	50	12	67.98	80.6	12.62
32					24	67.98	81.4	13.42
33					36	67.98	80.6	12.62
34				40	12	63.91	78.6	14.69
35					24	63.91	76.3	12.39
36					36	63.91	79.9	15.99
37				30	12	60.58	80.4	19.82
38					24	60.58	79.2	18.62
39					36	60.58	75.8	15.22
40			Road Quake	50	36	67.98	87.7	19.72
41				40	36	63.91	89.3	25.39
42				30	36	60.58	87.4	26.82
43	8strips/set	26' Truck	ATM	50	12	69.27	73.8	4.53
44					24	69.27	78	8.73
45					36	69.27	77.5	8.23
46				40	12	67.98	73.6	5.62
47					24	67.98	74.8	6.82
48					36	67.98	75.6	7.62
49				30	12	64.25	73.6	9.35
50					24	64.25	72.6	8.35
51					36	64.25	75.7	11.45
52			Swarco	50	12	69.27	82.2	12.93
53					24	69.27	79.8	10.53
54					36	69.27	75.7	6.43
55				40	12	67.98	80.2	12.22
56					24	67.98	75.3	7.32
57					36	67.98	79.4	11.42
58				30	12	64.25	73.2	8.95
59					24	64.25	77.5	13.25
60					36	64.25	76	11.75
61			Road Quake	50	36	69.27	84	14.73
62				40	36	67.98	83.5	15.52
63				30	36	64.25	88.6	24.35

Table F2 Sound Measurements of Rumble Strips Prior to Work Zones (6 strips/set)

Reading Number	Pattern	Vehicle Type	Rumble Strip Type	Speed Limit (mbh)	Spacing (inch)	Sound Readings		
						Ambient	Rumble	Effect (dBA)
64	6strips/set	Sedan	ATM	50	12	70.14	82.4	12.26
65					24	70.14	79.4	9.26
66					36	70.14	79.8	9.66
67				40	12	68.24	77.1	8.86
68					24	68.24	78.3	10.06
69					36	68.24	76.9	8.66
70				30	12	65.01	77.7	12.69
71					24	65.01	74.9	9.89
72					36	65.01	73.7	8.69
73			Swarco	50	12	70.14	83.9	13.76
74					24	70.14	82	11.86
75					36	70.14	82.3	12.16
76				40	12	68.24	80.7	12.46
77					24	68.24	79	10.76
78					36	68.24	79.4	11.16
79				30	12	65.01	77.3	12.29
80					24	65.01	77.1	12.09
81					36	65.01	74.5	9.49
82			Road Quake	50	36	70.14	84.7	14.56
83				40	36	68.24	83.1	14.86
84				30	36	65.01	86.8	21.79
85	6strips/set	Van	ATM	50	12	67.98	79	11.02
86					24	67.98	80.4	12.42
87					36	67.98	78.8	10.82
88				40	12	63.91	79.8	15.89
89					24	63.91	76.4	12.49
90					36	63.91	81.5	17.59
91				30	12	60.58	72.8	12.22
92					24	60.58	79.4	18.82
93					36	60.58	73	12.42
94			Swarco	50	12	67.98	81	13.02
95					24	67.98	78	10.02
96					36	67.98	79.8	11.82
97				40	12	63.91	74.9	10.99
98					24	63.91	74.7	10.79
99					36	63.91	80.5	16.59
100				30	12	60.58	76.9	16.32
101					24	60.58	79.2	18.62
102					36	60.58	72	11.42
103			Road Quake	50	36	67.98	84.9	16.92
104				40	36	63.91	87.4	23.49
105				30	36	60.58	88.4	27.82
106	6strips/set	26' Truck	ATM	50	12	69.27	76.7	7.43
107					24	69.27	76.7	7.43
108					36	69.27	78.2	8.93
109				40	12	67.98	72.7	4.72
110					24	67.98	73.6	5.62
111					36	67.98	75.9	7.92
112				30	12	64.25	74.3	10.05
113					24	64.25	80.9	16.65
114					36	64.25	82	17.75
115			Swarco	50	12	69.27	78.3	9.03
116					24	69.27	81.6	12.33
117					36	69.27	75.7	6.43
118				40	12	67.98	79.5	11.52
119					24	67.98	79.8	11.82
120					36	67.98	82	14.02
121				30	12	64.25	73.7	9.45
122					24	64.25	74.9	10.65
123					36	64.25	76.8	12.55
124			Road Quake	50	36	69.27	87.2	17.93
125				40	36	67.98	85.1	17.12
126				30	36	64.25	92.7	28.45

Table F3 Sound Measurements of Rumble Strips Prior to Work Zones (4 strips/set)

Reading Number	Pattern	Vehicle Type	Rumble Strip Type	Speed Limit (mbh)	Spacing (inch)	Sound Readings		
						Ambient	Rumble	Effect (dBA)
127	4strips/set	Sedan	ATM	50	12	70.14	81.6	11.46
128					24	70.14	79.8	9.66
129					36	70.14	82	11.86
130				40	12	68.24	79.8	11.56
131					24	68.24	78.8	10.56
132					36	68.24	77.9	9.66
133				30	12	65.01	76.5	11.49
134					24	65.01	74.7	9.69
135					36	65.01	76.1	11.09
136			Swarco	50	12	70.14	81.6	11.46
137					24	70.14	79.8	9.66
138					36	70.14	82	11.86
139				40	12	68.24	81.2	12.96
140					24	68.24	78.9	10.66
141					36	68.24	78.8	10.56
142				30	12	65.01	77.1	12.09
143					24	65.01	75.7	10.69
144					36	65.01	75.6	10.59
145			Road Quake	50	36	70.14	84.1	13.96
146				40	36	68.24	83.7	15.46
147				30	36	65.01	88.8	23.79
148	4strips/set	Van	ATM	50	12	67.98	76.1	8.12
149					24	67.98	76.5	8.52
150					36	67.98	76.1	8.12
151				40	12	63.91	77.3	13.39
152					24	63.91	76.7	12.79
153					36	63.91	78.6	14.69
154				30	12	60.58	69.4	8.82
155					24	60.58	75.3	14.72
156					36	60.58	73.1	12.52
157			Swarco	50	12	67.98	77	9.02
158					24	67.98	78	10.02
159					36	67.98	77.7	9.72
160				40	12	63.91	76.1	12.19
161					24	63.91	74.7	10.79
162					36	63.91	79.9	15.99
163				30	12	60.58	73.2	12.62
164					24	60.58	78	17.42
165					36	60.58	71.8	11.22
166			Road Quake	50	36	67.98	88.7	20.72
167				40	36	63.91	90.2	26.29
168				30	36	60.58	88.7	28.12
169	4strips/set	26' Truck	ATM	50	12	69.27	74.7	5.43
170					24	69.27	75.6	6.33
171					36	69.27	74.3	5.03
172				40	12	67.98	72.2	4.22
173					24	67.98	74.9	6.92
174					36	67.98	73.8	5.82
175				30	12	64.25	72.1	7.85
176					24	64.25	70.5	6.25
177					36	64.25	72.5	8.25
178			Swarco	50	12	69.27	74.9	5.63
179					24	69.27	78.8	9.53
180					36	69.27	75.2	5.93
181				40	12	67.98	74.3	6.32
182					24	67.98	74.5	6.52
183					36	67.98	75.5	7.52
184				30	12	64.25	71.6	7.35
185					24	64.25	73.4	9.15
186					36	64.25	74.9	10.65
187			Road Quake	50	36	69.27	83.7	14.43
188				40	36	67.98	83.8	15.82
189				30	36	64.25	89.7	25.45

Table F4 Sound Measurements of Rumble Strips at the Edge of Work Zones (8 strips/set)

Reading Number	Pattern	Vehicle Type	Rumble Strip Type	Speed Limit (mbh)	Spacing (inch)	Sound Readings		
						Ambient	Rumble	Effect (dBA)
190	8strips/set	Sedan	ATM	50	12	70.14	80.8	10.66
191					24	70.14	79.4	9.26
192					36	70.14	78.8	8.66
193				40	12	68.24	75.2	6.96
194					24	68.24	77.7	9.46
195					36	68.24	75.7	7.46
196				30	12	65.01	75.3	10.29
197					24	65.01	73.9	8.89
198					36	65.01	73.7	8.69
199			Swarco	50	12	70.14	85.4	15.26
200					24	70.14	78.8	8.66
201					36	70.14	82.9	12.76
202				40	12	68.24	79.9	11.66
203					24	68.24	76.9	8.66
204					36	68.24	75.9	7.66
205				30	12	65.01	74.1	9.09
206					24	65.01	74.5	9.49
207					36	65.01	73.7	8.69
208	8strips/set	Van	ATM	50	12	67.98	78.8	10.82
209					24	67.98	79.2	11.22
210					36	67.98	78.8	10.82
211				40	12	63.91	75.7	11.79
212					24	63.91	72.3	8.39
213					36	63.91	76	12.09
214				30	12	60.58	72.6	12.02
215					24	60.58	72.2	11.62
216					36	60.58	73.1	12.52
217			Swarco	50	12	67.98	75.5	7.52
218					24	67.98	76.1	8.12
219					36	67.98	77.1	9.12
220				40	12	63.91	74.7	10.79
221					24	63.91	72.8	8.89
222					36	63.91	73.2	9.29
223				30	12	60.58	73.2	12.62
224					24	60.58	77.1	16.52
225					36	60.58	68.7	8.12
226	8strips/set	26' Truck	ATM	50	12	69.27	74.7	5.43
227					24	69.27	74.3	5.03
228					36	69.27	74.1	4.83
229				40	12	67.98	73.4	5.42
230					24	67.98	71	3.02
231					36	67.98	71.8	3.82
232				30	12	64.25	69.8	5.55
233					24	64.25	70	5.75
234					36	64.25	74.9	10.65
235			Swarco	50	12	69.27	76.7	7.43
236					24	69.27	77	7.73
237					36	69.27	74.1	4.83
238				40	12	67.98	77.5	9.52
239					24	67.98	72.6	4.62
240					36	67.98	73.7	5.72
241				30	12	64.25	74.7	10.45
242					24	64.25	76.8	12.55
243					36	64.25	74.7	10.45

Table F5 Sound Measurements of Rumble Strips at the Edge of Work Zones (6 strips/set)

Reading Number	Pattern	Vehicle Type	Rumble Strip Type	Speed Limit (mbh)	Spacing (inch)	Sound Readings		
						Ambient	Rumble	Effect (dBA)
244	6strips/set	Sedan	ATM	50	12	70.14	80.4	10.26
245					24	70.14	78.2	8.06
246					36	70.14	78.3	8.16
247				40	12	68.24	74.9	6.66
248					24	68.24	80.1	11.86
249					36	68.24	74.3	6.06
250				30	12	65.01	73.6	8.59
251					24	65.01	73.6	8.59
252					36	65.01	74.7	9.69
253			Swarco	50	12	70.14	85.9	15.76
254					24	70.14	79	8.86
255					36	70.14	80.9	10.76
256				40	12	68.24	79.8	11.56
257					24	68.24	79.2	10.96
258					36	68.24	77.6	9.36
259				30	12	65.01	74.1	9.09
260					24	65.01	74.7	9.69
261					36	65.01	73.9	8.89
262	6strips/set	Van	ATM	50	12	67.98	78.2	10.22
263					24	67.98	77.5	9.52
264					36	67.98	75.9	7.92
265				40	12	63.91	72.6	8.69
266					24	63.91	70.6	6.69
267					36	63.91	74	10.09
268				30	12	60.58	68.6	8.02
269					24	60.58	72.2	11.62
270					36	60.58	72.5	11.92
271			Swarco	50	12	67.98	74.9	6.92
272					24	67.98	78	10.02
273					36	67.98	75.9	7.92
274				40	12	63.91	73.6	9.69
275					24	63.91	73.6	9.69
276					36	63.91	75.6	11.69
277				30	12	60.58	70.8	10.22
278					24	60.58	77.5	16.92
279					36	60.58	67.5	6.92
280	6strips/set	26' Truck	ATM	50	12	69.27	73.8	4.53
281					24	69.27	74.9	5.63
282					36	69.27	73.4	4.13
283				40	12	67.98	71.1	3.12
284					24	67.98	71.3	3.32
285					36	67.98	71.4	3.42
286				30	12	64.25	76.5	12.25
287					24	64.25	71.5	7.25
288					36	64.25	76	11.75
289			Swarco	50	12	69.27	74.9	5.63
290					24	69.27	76.5	7.23
291					36	69.27	74.1	4.83
292				40	12	67.98	74.4	6.42
293					24	67.98	73.7	5.72
294					36	67.98	75.4	7.42
295				30	12	64.25	70.8	6.55
296					24	64.25	71.8	7.55
297					36	64.25	73.6	9.35

Table F6 Sound Measurements of Rumble Strips at the Edge of Work Zones (4 strips/set)

Reading Number	Pattern	Vehicle Type	Rumble Strip Type	Speed Limit (mbh)	Spacing (inch)	Sound Readings		
						Ambient	Rumble	Effect (dBA)
298	4strips/set	Sedan	ATM	50	12	70.14	75.3	5.16
299					24	70.14	77.4	7.26
300					36	70.14	78.8	8.66
301				40	12	68.24	75.6	7.36
302					24	68.24	74.6	6.36
303					36	68.24	75.7	7.46
304				30	12	65.01	73.2	8.19
305					24	65.01	72.2	7.19
306					36	65.01	72.2	7.19
307			Swarco	50	12	70.14	78.8	8.66
308					24	70.14	76.7	6.56
309					36	70.14	80.6	10.46
310				40	12	68.24	74.9	6.66
311					24	68.24	76.2	7.96
312					36	68.24	77.8	9.56
313				30	12	65.01	70.9	5.89
314					24	65.01	73	7.99
315					36	65.01	73	7.99
316	4strips/set	Van	ATM	50	12	67.98	76.8	8.82
317					24	67.98	76.1	8.12
318					36	67.98	75.2	7.22
319				40	12	63.91	72	8.09
320					24	63.91	71	7.09
321					36	63.91	72.3	8.39
322				30	12	60.58	66.5	5.92
323					24	60.58	69.1	8.52
324					36	60.58	70.2	9.62
325			Swarco	50	12	67.98	74.9	6.92
326					24	67.98	75.3	7.32
327					36	67.98	74.9	6.92
328				40	12	63.91	72.6	8.69
329					24	63.91	70.6	6.69
330					36	63.91	72	8.09
331				30	12	60.58	68.6	8.02
332					24	60.58	71	10.42
333					36	60.58	69.4	8.82
334	4strips/set	26' Truck	ATM	50	12	69.27	71.6	2.33
335					24	69.27	72.8	3.53
336					36	69.27	72	2.73
337				40	12	67.98	70.1	2.12
338					24	67.98	70.6	2.62
339					36	67.98	69.8	1.82
340				30	12	64.25	68.4	4.15
341					24	64.25	69.3	5.05
342					36	64.25	70.1	5.85
343			Swarco	50	12	69.27	76.9	7.63
344					24	69.27	77.3	8.03
345					36	69.27	78	8.73
346				40	12	67.98	71.6	3.62
347					24	67.98	74	6.02
348					36	67.98	73.6	5.62
349				30	12	64.25	70.3	6.05
350					24	64.25	73.2	8.95
351					36	64.25	72.3	8.05